10. Assessment of the Northern Rockfish Stock in the Gulf of Alaska

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Executive Summary

We use a statistical age-structured model as the primary assessment tool for GOA northern rockfish which qualifies as a Tier 3 stock. This assessment consists of a population model, which uses survey and fishery data to generate a historical time series of population estimates, and a projection model, which uses results from the population model to predict future population estimates and recommended harvest levels. The data sets used in this assessment include total catch biomass, fishery age and size compositions, trawl survey abundance estimates, and trawl survey age compositions. For Gulf of Alaska northern rockfish in 2022, we present a full assessment with updated assessment and projection model results to recommend harvest levels for the next two years.

Summary of Changes in Assessment Inputs

Changes to input data: Relative to the last full assessment the following substantive changes have been made to assessment inputs:

- include survey biomass estimates for 2021,
- update survey age compositions with 2021 data,
- update fishery age compositions with 2020 data,
- update final catch values for 2020 and 2021, and use preliminary catch for 2022.

The survey biomass estimate is based upon the Groundfish Assessment Program's Vector Autoregressive Spatio-temporal (VAST) model for the GOA through 2021.
Survey data from the 1980s were excluded from this assessment. In the last few assessments survey biomass from 1984 and 1987 have been included in the survey biomass estimate (though not in the compositional data), however those surveys used different vessels and gear and are not directly comparable to survey data from 1990+. Removal of these data had minimal effects on model performance and they have been excluded from this assessment going forward.

Changes in assessment methodology: The following model change is recommended in the current assessment: extend the length plus group from 38 cm to 45 cm.

Summary of Results

A suite of incremental models were run to investigate the effects of removing 1980s survey data from the assessment, increasing the length plus group, re-weighting of compositional data, and changing the survey biomass weight from 0.25 to 1.0.

Model	Description
base	2020 model (m18.2b) and results (includes 1980s survey data)
m18.2b	base model w/data updated through 2022, using GAP default VAST
m22	m18.2b using GAP default VAST (survey data 1990+)
m22.1	m22 w/increased length plus group
m22.1a	m22.1 w/Francis re-weighting
m22.1b	m22.1a w/survey biomass weight set to 1

The author's preferred model is m22.1, which is the 2020 model with updated data through 2022, and an increased length plus group that uses a VAST model-based index of survey abundance with GAP default settings. This model generally produces good visual fits to the data and biologically reasonable patterns of recruitment, abundance, and selectivity, and relatively low retrospective Mohn's rho value.

The m22.1 projected age 2+ total biomass for 2023 is 95,452 t. The recommended ABC for 2023 is 4,965 t, the maximum allowable ABC under Tier 3a. This ABC is a 4% decrease compared to the 2022 ABC of 5,147 t and a 1% increase from the projected 2023 ABC from last year. The 2023 GOA-wide OFL for northern rockfish is 5,927 t.

The stock is not being subject to overfishing, is not currently overfished, nor is it approaching a condition of being overfished.

Reference values for northern rockfish are summarized in the following table:

	As estimated or *specified last* year for:		As estimated or *recommended this* year for:	
Quantity/Status	2022	2023	2023*	2024*
M (natural mortality)	0.059	0.059	0.059	0.059
Tier	3a	3a	3a	3a
Projected total (age 2+) biomass (t)	100,371	96,045	95,452	93,022
Projected female spawning biomass (t)	40,474	37,408	39,445	37,470
$B_{100\%}$	84,832	84,832	82,350	82,350
$B_{40\%}$	33,933	33,933	32,940	32,940
$B_{35\%}$	29,691	29,691	28,822	28,822
F_{OFL}	0.073	0.073	0.074	0.074
$maxF_{ABC}$	0.061	0.061	0.061	0.061
F_{ABC}	0.061	0.061	0.061	0.061
OFL (t)	6,143	5,874	5,927	5,661
*max*ABC (t)	5,147	4,921	4,965	4,742
ABC (t)	5,147	4,921	4,965	4,742
	As determined *last* year for:		As determined *this* year for:	
Status	2021	2022	2022	2023
Overfishing	No	n/a	No	n/a
Overfished	n/a	No	n/a	No
Approaching overfished	n/a	No	n/a	No

*Projections are based on an estimated catch of 2,003 t for 2022 and estimates of 2,654 t and 2,464 t used in place of maximum permissible ABC for 2023 and 2024.

Area Allocation of Harvest

The following table shows the recommended ABC apportionment for 2022 and 2023. Apportionment is based on the random effects model developed by Plan Team survey averaging working group, which was fit to area-specific design-based biomass indices through 2021 from the bottom trawl survey.

		Western	Central	Eastern[1]	Total
Year	Area Apportionment	52.65%	47.33%	0.02%	100%
2023	ABC (t)	2,614	2,350	1	4,965
2023	OFL (t)				5,927
2024	ABC (t)	2,497	2,244	1	4,742
2024	OFL (t)				5,661

[1]For management purposes the small ABC in the Eastern area is combined with the Other Rockfish complex.

Responses to SSC and Plan Team Comments on Assessments in General

"The SSC requests that all authors fill out the risk table in 2019…" (SSC December 2018)

A risk table has been included in this full assessment.

"The Team recommends all GOA authors evaluate any bottom trawl survey information used in their assessment prior to 1990 including the 1984 and 1987 surveys and conduct sensitivity analyses to evaluate their usefulness to the assessment. This may apply for Aleutian Islands surveys but this was only raised during GOA assessment considerations." (PT, November 2021)

In recent assessments survey biomass estimates from 1984 and 1987 (note that age and size composition data were not included) have been included in the survey biomass estimate, however those surveys used different vessels and gear and are not directly comparable to survey data from 1990+. A suite of incremental models were run to investigate the effects of removing 1980s survey data from the assessment and removal of these surveys has minimal effect on derived quantities in recent years. Therefore they have been excluded from this assessment going forward.

Responses to SSC and Plan Team Comments Specific to this Assessment

The Team recommends evaluating how the definition of the length composition plus group, and alternative data-weighting methods, affect model performance." (Plan Team, November 2015); "Finally, the SSC notes the increasing proportion of fish in the fishery length composition plus-group and looks forward to seeing the results of the ongoing investigations into alternative length composition bin structures. The SSC also agrees with the high priority placed on improving maturity-at-age information for northern rockfish." (SSC, December 2018)

The authors have increased the length plus group by 5 cm and present finding as the author's recommended model. Alternative data-weightings have been examined and are presented but not selected as the preferred model at this time. Skip spawning has been observed for northern rockfish, however the spatial and temporal extent are unknown. A preliminary examination of spawning biomass estimates with skip spawning is included in the figures, though further examination is warranted.

Introduction

Biology and Distribution

Northern rockfish, *Sebastes polyspinis*, is a locally abundant and commercially valuable member of its genus in Alaskan waters. As implied by its common name, northern rockfish has one of the most northerly distributions among the 60+ species of *Sebastes* in the North Pacific Ocean. It ranges from extreme northern British Columbia around the northern Pacific Rim to eastern Kamchatka and the northern Kuril Islands and also north into the eastern Bering Sea (Allen and Smith 1988). Within this range, northern rockfish are most abundant in Alaska waters, from the western end of the Aleutian Islands to Portlock Bank in the central Gulf of Alaska (GOA; Clausen and Heifetz 2002).

Little is known about the life history of northern rockfish. Like other Sebastes species, northern rockfish are presumed to be ovoviviparous with internal fertilization. There have been no studies on fecundity of northern rockfish. Observations during research surveys in the GOA indicate that parturition (larval release) occurs in the spring and is completed by summer. Larval northern rockfish cannot be unequivocally identified to species at this time, even using genetic techniques, so information on larval distribution and length of the larval stage is unknown. The larvae metamorphose to a pelagic juvenile stage, but there is no information on when these juveniles become demersal.

Little information is available on the habitat of juvenile northern rockfish. Studies in the eastern GOA and Southeast Alaska using trawls and submersibles have indicated that several species of juvenile (< 20 cm) red rockfish (Sebastes spp.) associate with benthic nearshore living and non-living structure and appear to use the structure as a refuge (Carlson and Straty 1981; Krieger 1993). Freese and Wing (2003) also identified juvenile (5 to 10 cm) red rockfish (*Sebastes spp*.) associated with sponges (primarily *Aphrocallistes spp.*) attached to boulders 50 km offshore in the GOA at 148 m depth over a substrate that was primarily a sand and silt mixture. Only boulders with sponges harbored juvenile rockfish, and the juvenile red rockfish appeared to be using the sponges as shelter (Freese and Wing 2003). Although these studies did not specifically observe northern rockfish, it is likely that juvenile northern rockfish also utilize similar habitats. Length frequencies of northern rockfish captured in NMFS bottom trawl surveys and observed in commercial fishery bottom trawl catches indicate that older juveniles (>20 cm) are found on the continental shelf, generally at locations inshore of the adult habitat (Pers. comm. Dave Clausen).

Northern rockfish are generally planktivorous. They eat mainly euphausiids and calanoid copepods in both the GOA and the Aleutian Islands (Yang 1993, 1996, 2000). There is no indication of a shift in diet over time or a difference in diet between the GOA and AI Yang (2000). In the Aleutian Islands, calanoid copepods were the most important food of smaller-sized northern rockfish (< 25 cm), while euphausiids were the main food of larger sized fish (> 25 cm) (Yang 1996). The largest size group also consumed myctophids and squids (Yang 2000). Arrow worms, hermit crabs, and shrimp have also been noted as prey items in much smaller quantities Yang (1996). Large offshore euphausiids are not directly associated with the bottom, but rather, are thought to be advected onshore near bottom at the upstream ends of underwater canyons where they become easy prey for planktivorous fishes Brodeur (2001)]. Predators of northern rockfish are not well documented, but likely include larger fish, such as Pacific halibut, that are known to prey on other rockfish species.

Trawl surveys and commercial fishing data indicate that the preferred habitat of adult northern rockfish in the GOA is relatively shallow rises or banks on the outer continental shelf at depths of about 75-150 m (Clausen and Heifetz 2002). The highest concentrations of northern rockfish from NMFS trawl survey catches appear to be associated with relatively rough (variously defined as hard, steep, rocky or uneven) bottom on these banks (Clausen and Heifetz 2002). Heifetz (2002) identified rockfish as among the most common commercial fish captured with gorgonian corals (primarily *Callogorgia*, *Primnoa*, *Paragorgia*, *Fanellia*, *Thouarella*, and *Arthrogorgia*) in NMFS trawl surveys of GOA and Aleutian waters. Krieger and Wing (2002) identified six rockfish species associated with gorgonian coral (*Primnoa spp*.) from a manned submersible in the eastern GOA. Research focusing on untrawlable habitats found rockfish species often associate with biogenic structure (Du Preez and Tunnicliffe 2011; Laman *et al.* 2015). However, most of these studies did not specifically observe northern rockfish, and more research is required to determine if northern rockfish are associated with living structure, including corals, in the GOA, and the nature of those associations if they exist. Recent work on black rockfish (Sebastes melanops) has shown that larval survival may be higher from older female spawners (Berkeley *et al.* 2004). The black rockfish population has shown a distinct reduction in the proportion of older fish in recent fishery samples off the West Coast of North America, raising concerns if larval survival diminishes with lower spawner age. Bruin *et al.* (2004) examined Pacific ocean perch (*S. alutus*) and rougheye rockfish (*S. aleutianus*) for senescence in reproductive activity of older fish and found that oogenesis continues at advanced ages. Leaman (1991) showed that older individuals have slightly higher egg dry weight than their middle-aged counterparts. Some literature suggests that environmental factors may affect the condition of female rockfish that contributes to reproductive success (Hannah and Parker 2007; Rodgveller *et al.* 2012; Beyer *et al.* 2015). However, relationships on fecundity or larval survival at age have not yet been evaluated for northern rockfish or other rockfish in Alaska. Stock assessments for Alaska groundfish have assumed that the reproductive success of mature fish is independent of age.

Stock Structure

GOA northern rockfish grow significantly faster and reach a larger maximum length than Aleutian Islands northern rockfish (Clausen and Heifetz 2002). Also, Aleutian Islands northern rockfish are slightly older (maximum age-72) than GOA northern rockfish (maximum age-67), the difference in age could be due to sampling variability. There have been two studies on the genetic stock structure of northern rockfish. One study of northern rockfish provided no evidence for genetically distinct stock structure when comparing samples from near the western Aleutian Islands, the western GOA, and Kodiak Island (Gharrett *et al.* 2003). The results from that study were considered preliminary, and sample sizes were small. Consequently, the lack of evidence for stock structure did not necessarily confirm stock homogeneity. A more recent study did find spatial structure on a relatively small scale for northern rockfish sampled from several locations in the Aleutian Islands and Bering Sea (Gharrett *et al.* 2012).

Results of an analysis of localized depletion based on Leslie depletion estimators on targeted rockfish catches detected relatively few localized depletions for northern rockfish (Hanselman *et al.* 2007). Several significant depletions occurred in the early 1990s for northern rockfish, but were not detected again by the depletion analysis. However, when fishery and survey CPUEs were plotted over time for a geographic block of high rockfish fishing intensity that contained the “Snakehead” area, the results indicated there were year-after-year drops in both fishery and survey CPUE for northern rockfish. The significance of these observations depends on the migratory and stock structure patterns of northern rockfish. If fine-scale stock structure is determined in northern rockfish, or if the area is essential to northern rockfish reproductive success, then these results would suggest that current apportionment of ABC may not be sufficient to protect northern rockfish from localized depletion. Provisions to guard against serial depletion in northern rockfish should be examined in the GOA rockfish rationalization plan. The extension of the fishing season that has been implemented may spread out the fishery in time and space and reduce the risk of localized serial depletion on the “Snakehead” and other relatively shallow (75 – 150 m) offshore banks on the outer continental shelf where northern rockfish are concentrated.

If there is relatively small scale stock structure (120 km) in GOA northern rockfish, then recovery from localized depletion, as indicated above for a region known as the “Snakehead,” could be slow. Analysis of otolith microchemistry may provide a useful tool, in addition to genetic analysis, for identifying small scale (120 km) stock structure of northern rockfish relative to their overall range. Berkeley *et al.* (2004) suggests that, in addition to the maintenance of age structure, the maintenance of spatial distribution of recruitment is essential for long-term sustainability of exploited rockfish populations. In particular, Berkeley *et al.* (2004) outline Hedgecock’s “sweepstakes hypothesis” to explain small-scale genetic heterogeneity observed in some widely distributed marine populations. According to Berkeley *et al.* (2004), “most spawners fail to produce surviving offspring because their reproductive activity is not matched in space and time to favorable oceanographic conditions for larval survival during a given season. As a result of this mismatch the surviving year class of new recruits is produced by only a small minority of adults that spawned within those restricted temporal and spatial oceanographic windows that offered good conditions for larval survival and subsequent recruitment”. However, Miller and Shanks (2004) found limited larval dispersal (120 km) in black rockfish off the Pacific coast with an analysis of otolith microchemistry. In particular, these results suggest that black rockfish exhibit some degree of stock structure at very small scales (120 km) relative to their overall range. Localized genetic stocks of Pacific ocean perch have also been found in northern B.C. (Withler *et al.* 2001), and (Kamin *et al.* 2013) concluded that fine-scale genetic heterogeneity for Pacific ocean perch in Alaska was not the influence of a sweepstakes effect. Limited larval dispersal contradicts Hedgecock’s hypothesis and suggests that genetic heterogeneity in rockfish may be the result of stock structure rather than the result of the sweepstakes hypothesis.

Fishery

Description of the Directed Fishery

In the Gulf of Alaska, northern rockfish are generally caught with bottom trawls identical to those used in the Pacific ocean perch (*S. alutus*) fishery. Many of these nets are equipped with so-called “tire gear” in which automobile tires are attached to the footrope to facilitate towing over rough substrates. Most of the catch has been taken during July, as the directed rockfish trawl fishery in the GOA has traditionally opened around July 1. Rockfish trawlers usually direct their efforts first toward Pacific ocean perch because of its higher value relative to other rockfish species. After the TAC for Pacific ocean perch has been reached and NMFS closes directed fishing for this species, trawlers switch and target northern rockfish. With implementation of the Central Gulf Rockfish Pilot Project in 2007, catches have been spread out more throughout the year.

Historically, bottom trawls have accounted for nearly all the commercial harvest of northern rockfish in the GOA. In the years 1990-98, bottom trawls took over 99% of the catch (Clausen and Heifetz 2002). Before 1996, most of the slope rockfish trawl catch (>90%) was taken by large factory-trawlers that processed the fish at sea. A significant change occurred in 1996, however, when smaller shore-based trawlers began taking a sizable portion of the catch in the Central Gulf for delivery to processing plants in Kodiak. Factory trawlers continued to take nearly all the northern rockfish catch in the Western area during this period.

A study of the northern rockfish fishery for the period 1990-98 showed that 89% of northern rockfish catch was taken from just five relatively small fishing grounds: Portlock Bank, Albatross Bank, an unnamed bank south of Kodiak Island that fishermen commonly refer to as the “Snakehead”, Shumagin Bank, and Davidson Bank (Clausen and Heifetz 2002). The Snakehead accounted for 46% of the northern rockfish catch during these years. All of these grounds can be characterized as relatively shallow (75–150 m) offshore banks on the outer continental shelf.

Data from the observer program for 1990-98 indicated that 82% of the northern rockfish catch during that period came from directed fishing for northern rockfish and 18% was taken as incidental catch in fisheries for other species (Clausen and Heifetz 2002).

Catch Patterns

Total commercial catch (t) of northern rockfish in the GOA for the years 1961-2018 is summarized by foreign, joint venture, and domestic fisheries (Table 10-1 and Figure 10-1). Catches of GOA northern rockfish during the years 1961-1976 were estimated as 5% of the foreign GOA Pacific ocean perch catch in the same years. A Pacific ocean perch trawl fishery by the U.S.S.R. and Japan began in the GOA in the early 1960’s. This fishery developed rapidly with massive efforts by the Soviet and Japanese fleets. Catches peaked in 1965 when a total of nearly 350,000 metric tons (t) were caught, but declined to 45,500 t by 1976. Some northern rockfish were likely taken in this fishery, but there are no available summaries of northern rockfish catches for this period. Foreign catches of all rockfish were often reported simply as “Pacific ocean perch” with no attempt to differentiate species. The only detailed analysis of bycatch in slope rockfish fisheries of the GOA is that of Ackley and Heifetz (2001) who examined data from the observer program for the years 1993-95. Consequently, our best estimate of northern rockfish catch from 1961-1976 comes from analysis of the ratio of northern rockfish catch to Pacific ocean perch catch in the years 1993-1995. For hauls targeting on Pacific ocean perch, northern rockfish composed 5% of the catch (Ackley and Heifetz 2001).

Catches of GOA northern rockfish during the years 1977-1983 were available from NMFS foreign and joint venture fisheries observer data. With the advent of a NMFS observer program aboard foreign fishing vessels in 1977, enough information on species composition of rockfish catches was collected so that estimates of the northern rockfish catch were made for 1977-83 from extrapolation of catch compositions from the foreign observer program (Clausen and Heifetz 2002). The relatively large catch estimates for the foreign fishery in 1982-83 are an indication that at least some directed fishing for northern rockfish probably occurred in those years. Joint venture catches of northern rockfish, however, appear to have been relatively modest.

Catches of GOA northern rockfish during the years 1984-1989 were estimated as 8% of the domestic slope rockfish catch during the same years. A completely domestic trawl fishery for rockfish in the GOA began in 1984 but a domestic observer program was not implemented until 1990. Domestic catches of GOA northern rockfish during the years 1984-1989 were estimated from the ratio of domestic northern rockfish catch to domestic slope rockfish catch (8%) reported by the 1990 NMFS observer program.

Catches of GOA northern rockfish during the years 1990-1992 were estimated from extrapolation of catch compositions from the domestic observer program (Clausen and Heifetz 2002). Catch estimates of northern rockfish increased greatly from about 1,700 t in 1990 to nearly 7,800 t in 1992. The increases for 1991 and 1992 can be explained by the removal of Pacific ocean perch and shortraker/rougheye rockfish from the slope rockfish management group. As a result of this removal, relatively low TAC's were adopted for these three species, and the rockfish fleet redirected more of its effort to northern rockfish in 1991 and 1992.

Catches of GOA northern rockfish during the years 1993-2022 were available directly from NMFS domestic fisheries observer data. Northern rockfish were removed from the slope rockfish assemblage and managed with an individual TAC beginning in 1993. As a consequence, directly reported catch for northern rockfish has been available since 1993. Catch of northern rockfish was reduced after the implementation of a northern specific TAC in 1993. Most of the catch since 1993 has been taken in the Central GOA, where the majority of the northern rockfish exploitable biomass is located. GOA-wide catches for the years 1993-2022 have ranged from 1,835 t to 5,966 t. Annual ABCs and TACs have been relatively consistent during this period and have varied between 3,000–6,000 t. In 2001, catch of northern rockfish was below TAC because the maximum allowable bycatch of Pacific halibut was reached in the central GOA for "deep water trawl species," which includes northern rockfish. Catches of northern rockfish were near their TAC's in 2003 – 2016, however in 2017 catch was 48% of the TAC and 2022 projected catch is likely to reach 53% of the TAC. Consultation with industry representatives suggested the low catch to TAC ratio in 2017 was largely driven by the fleet targeting alternative higher value species. Research catches of northern rockfish have been relatively small and are listed in Table 10a-1 in Appendix 10A.

Bycatch and Discards

The only detailed analysis of incidental catch in slope rockfish fisheries of the GOA is that of Ackley and Heifetz (2001) who examined data from the observer program for the years 1993-95. For hauls targeting on northern rockfish, the predominant incidental species were dusky rockfish, distantly followed by "other slope rockfish," Pacific ocean perch, and arrowtooth flounder.

Total FMP groundfish catch estimates in the GOA rockfish fishery from 2018–2022 are shown in Table 10-2. As an average for the GOA rockfish fishery during 2018–2022, the largest non-rockfish bycatch groups are arrowtooth flounder, sablefish, atka mackerel and walleye pollock. Non-FMP species catch in the rockfish target fisheries is dominated by giant grenadier (*Albatrossia pectoralis*) and miscellaneous fish (Table 10-3). However, the amounts from northern rockfish targeted hauls are likely lower as this includes all rockfish target hauls.

Prohibited species catch in the GOA rockfish fishery is generally low for most species. Catch of prohibited and non-target species generally decreased with implementation of the Central GOA Rockfish

Program. Since the 2020 assessment the prohibited species catch observed in 2021 and 2022 increased for Chinook salmon and non-chinook salmon increased, and remained at similar levels for halibut (Table 10-4).

In summary, northern rockfish are most likely to be associated with other rockfish fisheries and the bycatch of non-rockfish species in the northern rockfish fishery are likely low but the only data available is for all rockfish-targeted hauls. Bycatch estimates decreased for the majority of species in the Central GOA following the implementation of the Rockfish Pilot Program. The significant prohibited species that are encountered are Pacific halibut, Chinook and non-Chinook salmon.

Gulf-wide discard rates (percent of the total catch discarded within management categories; Table 10-5) of northern rockfish are show for 1993–2022. These rates are generally considered to be low and are consistent with other GOA rockfish species. These discard rates are generally similar to those in the GOA for Pacific ocean perch and dusky rockfish. Discard mortality is assumed to be 100% for GOA northern rockfish.

Management Measures

From 1988-1993, the North Pacific Fishery Management Council (NPFMC) managed northern rockfish in the GOA as part of the slope rockfish assemblage. In 1991, the NPFMC divided the slope rockfish assemblage in the GOA into three management subgroups: Pacific ocean perch, shortraker/rougheye rockfish, and a complex of all other species of slope rockfish, including northern rockfish. In 1993, a fourth management subgroup, northern rockfish, was also created. In 2004, rougheye rockfish and shortraker rockfish were also split and managed separately. These subgroups were established to protect Pacific ocean perch, shortraker/rougheye, and northern rockfish (the four most sought-after commercial species in the assemblage) from possible overfishing. Each subgroup is now assigned an individual ABC (acceptable biological catch) and TAC (total allowable catch). Prior to 1991, an ABC and TAC were assigned to the entire assemblage. In the assessments after 1991 and until this year's assessment, ABC and TAC for each subgroup, including northern rockfish, is apportioned to the three management areas of the GOA (Western, Central, and Eastern) based on a weighted average of the proportion of biomass by area from the three most recent GOA trawl surveys. In this year's assessment ABC and TAC is apportioned to the three management areas using the random effects model developed by the Plan Team survey averaging working group. Northern rockfish are scarce in the eastern GOA and the ABC apportioned to the Eastern Gulf management area is small. This translates to a TAC that is too difficult to be managed effectively as a directed fishery. Since 1999, the ABC for northern rockfish apportioned to the Eastern Gulf management area is included in the West Yakutat ABC for "other slope rockfish."

Amendment 41, which took effect in 2000, prohibited trawling east of 140 degrees W. longitude in the Eastern GOA. However, trawling has not occured in this area since 1998. Since most slope rockfish, especially Pacific ocean perch, are caught exclusively with trawl gear, this amendment could have concentrated fishing effort for slope rockfish in the Eastern area in the relatively small area between 140° and 147° W longitude that remained open to trawling. This probably does not have a major effect on northern rockfish populations because their abundance in the Eastern area is low.

In November, 2006, NMFS issued a final rule to implement Amendment 68 of the GOA groundfish Fishery Management Plan for 2007 through 2011. This action implemented the Central GOA Rockfish Pilot Program (RPP). The intention of this Program was to enhance resource conservation and improve economic efficiency for harvesters and processors in the rockfish fishery. An additional objective was to spread out the fishery in time and space, allowing for enhanced market conditions for product and reducing the pressure of what was an approximately two-week fishery in July. The primary rockfish management groups in this program are northern rockfish, Pacific ocean perch, and pelagic shelf rockfish. Potential effects of this program on northern rockfish include: 1) Extended fishing season lasting from

May 1 – November 15, 2) changes in spatial distribution of fishing effort within the Central GOA, 3) improved at-sea and plant observer coverage for vessels participating in the rockfish fishery, and 4) a higher potential to harvest 100% of the TAC in the Central GOA region. In a comparison of catches in the four years before the RPP to the four years after, it appears that average catches have increased overall (although, this may be due to increased observer coverage) and have spread out spatially in the western and central Gulf (see Figure 10.1 in Hulson *et al.* 2013). The authors will continue to monitor the benefits and consequences of this action. A summary of key management measures and a time series of catch, ABC and TAC are provided in Table 10-6.

Data

The following table summarizes the data used in the stock assessment model for northern rockfish (**bold** denotes new data for this assessment):

Source	Data	Years
NMFS Groundfish survey	Survey biomass	1990-1999 (triennial), 2001-2019 (biennial), **2021**
	Age composition	1990-1999 (triennial), 2003-2019 (biennial), **2021**
U.S. trawl fishery	Catch	1961-2020, **2021-2022**
	Age composition	1998-2002, 2004-2006, 2008-2018 (biennial), **2020**
	Length composition	1991-1997, 2003, 2007-2019 (biennial), **2021**

Fishery

Catch

Catch of northern rockfish ranges from 185 t to 17,430 t during 1961-2022. Detailed descriptions of catch are provided in Table 10-1 and Figure 10-1. This is the commercial catch history used in the assessment model. In response to Annual Catch Limits (ACLs) requirements, assessments now document all removals including catch that is not associated with a directed fishery. Estimates of all removals not associated with a directed fishery including research catches are available and are presented in Appendix 10a. In summary, annual research removals have typically been less than 100 t and very little is taken in recreational or Pacific halibut fisheries. These levels likely do not pose a significant risk to the northern rockfish stock in the GOA.

Age and Size Composition

Observers aboard fishing vessels and at onshore processing facilities have provided data on size and age composition of the commercial catch of northern rockfish. Ages were determined from the break-and-burn method (Chilton and Beamish 1982). Length compositions are presented in Table 10-7 and Figure 10-2 and age compositions are presented in Table 10-8 and Figure 10-8; these tables also include associated annual sample sizes and number of hauls sampled for the age and length compositions. The fishery age compositions indicate that stronger than average year-classes occurred around the year 1976 and 1984. The fishery age compositions from 2004 and 2006 also indicate that the 1996-1998 year-classes were strong. There are few younger fish observed in the age compositions for more recent years. The clustering of several large year-classes in each period is most likely due to aging error. Recent fishery length compositions (2003-present) indicate that a large proportion of the northern rockfish catch are found to be larger than 38 cm, which was the previous plus length bin. Length composition data show a slight increase in the size of fish caught, this is well aligned with the lack of younger fish observed in the fishery age compositions for the same time periods.

Survey

Biomass Estimates from Trawl Surveys

Bottom trawl surveys were conducted in the GOA triennially from 1984–1999 and biennially from since 2001. The surveys provide an index of biomass, size and age composition data, and growth characteristics. The trawl surveys have used a stratified random design to sample fishing stations that cover all areas of the GOA out to a depth of 1,000 m (in some surveys only to 500 m). Generally, attempts have been made through the years to standardize the survey design and the fishing nets used, but there have been some exceptions to this standardization. In particular, much of the survey effort in 1984 and 1987 was by Japanese vessels that used a very different net design and a different survey design than what has been the standard used by U.S. vessels throughout the surveys. To deal with this problem the 1980s survey data have been excluded from this assessment.

Gulf-wide biomass estimates from the VAST model-based index are presented in Table 10-9 and Figure 10-4. The author's preferred model uses VAST with a lognormal error distribution to model positive catch rates instead of the GAP default gamma distribution (see Appendix 10b). The spatial distribution of the catches of northern rockfish in the 2017, 2019, and 2021 surveys are shown in Figure 10-5. The magnitude of catch varies greatly with several large tows typically occurring in each survey. The precision of some of the biomass estimates has been low and is reflected in the high CVs associated with some survey biomass estimates of northern rockfish that are the result of few very large catches during the survey. In 2001, a single very large survey haul of northern rockfish greatly increased the biomass estimates and resulted in wide confidence bounds. The haul in 2001 was the largest individual catch (14 t) of northern rockfish ever taken during a GOA survey; this tow accounted for 58.7% of total survey catch by mass in that year. In contrast, the 2005 and 2007 survey had several large hauls of northern rockfish in the Central Gulf with similar confidence bounds. Due to the substantial variability observed in the design-based index this assessment is using the VAST model-based index of abundance, though trawl survey biomass from a design-based estimator is also presented per SSC request (Table 10-10).

Age and Size Composition

Ages for northern rockfish were determined from the break-and-burn method (Chilton and Beamish 1982). These age compositions (Table 10-11 and Figure 10-6) indicate that recruitment of northern rockfish is highly variable. The 1990 and 1996 surveys show especially strong year-classes from the period around 1975-77; although they differ as to which specific years were greatest, likely due to age determination errors. The 1993, 1996, and 1999 age compositions also indicate that the 1983-85 year-classes may be stronger than average. Recent age compositions (2005-2011) indicate that the 1996-98 year-classes may also be stronger than average, which is in agreement with recent age compositions obtained from the commercial fishery described above. Trawl surveys provide size composition data for northern rockfish but are not used directly in the current age structured assessment model (Table 10-12 and Figure 10-7). In years with age readings, trawl survey size composition data are multiplied by an age-length key (computed from length-stratified otolith collections) to obtain survey age compositions. Similar to the fishery length compositions discussed above, a large proportion of northern rockfish lengths are greater than the previous plus length bin (38 cm); especially in recent years. However, this issue has been addressed with the increased plus size group in this assessment. Also similar to the fishery age compositions, the proportion of older fish been increasing since the mid to early 2000s with few younger fish observed.

Maturity Data

In previous stock assessments for northern rockfish, age at maturity was based on a logistic curve fit to ovarian samples collected from female northern rockfish in the central GOA in the spring of 1996 (n=75,

C. Lunsford pers. comm. July 1997, Heifetz et al. 2009). A study reevaluating maturity of northern rockfish (Chilton 2007, n=157) provides additional information for maturity-at-age. This study collected ovarian samples from female northern rockfish throughout the year in both 2000 and 2001. In a report submitted to the GOA Groundfish Plan Team in September 2010, the two studies were compared and the advantages and disadvantages of the different approaches for studying maturity (histology versus visual inspection) were discussed (Rodgveller *et al.* 2013). In this year's assessment, as in the 2020 assessment, we combine the data from both studies to estimate maturity of northern rockfish. Due to the relatively small sample sizes for each study, the close proximity in time for each study (4 years apart compared to the 51 year time series used in this assessment), and the large difference in the age at 50% maturity (12.8 years used in previous assessments compared to 8 years obtained by Chilton 2007), we combine these data and estimate an intermediate maturity-at-age rather than consider time-dependent changes in maturity (Figure 10-8). There could be time-dependent changes in maturity-at-age for northern rockfish, although, additional data would be necessary to evaluate this hypothesis. More recently, Conrath (2019) has reported skip spawning in northern rockfish, the impacts of which are not currently incorporated into the assessment as the spatial and temporal aspects are unknown.

Analytical approach

General Model Structure

The basic model for GOA northern rockfish is described as a separable age-structured model and was implemented using AD Model Builder software (Fournier *et al.* 2012). The assessment model is based on a generic rockfish model developed in a workshop held in February 2001 (Courtney *et al.* 2007) and follows closely the GOA Pacific ocean perch model (Hulson *et al.* 2021). The northern rockfish model is fit to a time series extending from 1961-2022. As with other rockfish age-structured models, this model does not attempt to fit a stock-recruitment relationship but estimates a mean recruitment, which is adjusted by estimated recruitment deviations for each year. We do this because there does not appear to be an obvious stock-recruitment relationship in the model estimates, and there have been very high recruitments at low stock size (Figure 10-9). The parameters, population dynamics, and equations of the model are shown below:

BOX 1. AD Model Builder Model Description

Parameter definitions	
y	Year
a	Age classes
l	Length classes
w_a	Vector of estimated weight at age, $a_0 \rightarrow a_+$
m_a	Vector of estimated maturity at age, $a_0 \rightarrow a_+$
a_0	Age at first recruitment
a_+	Age when age classes are pooled
μ_r	Average annual recruitment, log-scale estimation
μ_f	Average fishing mortality
σ_r	Annual recruitment deviation
ϕ_y	Annual fishing mortality deviation
fs_a	Vector of selectivities at age for fishery, $a_0 \rightarrow a_+$
ss_a	Vector of selectivities at age for survey, $a_0 \rightarrow a_+$
M	Natural mortality
$F_{y,a}$	Fishing mortality for year y and age class a ($fs_a \mu_f e^{\varepsilon}$)
$Z_{y,a}$	Total mortality for year y and age class a ($=F_{y,a}+M$)
$\varepsilon_{y,a}$	Residuals from year to year mortality fluctuations
$T_{a,a'}$	Aging error matrix
$T_{a,l}$	Age to length transition matrix
q	Survey catchability coefficient
SB_y	Spawning biomass in year y, ($=m_a\, w_a\, N_{y,a}$)
q_{prior}	Prior mean for catchability coefficient
$\sigma_{r(prior)}$	Prior mean for recruitment deviations
σ_q^2	Prior CV for catchability coefficient
$\sigma_{\sigma_r}^2$	Prior CV for recruitment deviations

BOX 1 (Continued)

Equations describing the observed data

$$\hat{C}_y = \sum_a \frac{N_{y,a} * F_{y,a} * \left(1 - e^{-Z_{y,a}}\right)}{Z_{y,a}} * w_a$$ Catch equation

$$\hat{I}_y = q \; * \sum_a N_{y,a} * \frac{s_a}{\max\left(s_a\right)} * w_a$$ Survey biomass index (t)

$$\hat{P}_{y,a'} = \sum_a \left(\frac{N_{y,a} * s_a}{\sum_a N_{y,a} * s_a} \right) * T_{a,a'}$$ Survey age distribution
Proportion at age

$$\hat{P}_{y,l} = \sum_a \left(\frac{N_{y,a} * s_a}{\sum_a N_{y,a} * s_a} \right) * T_{a,l}$$ Survey length distribution
Proportion at length

$$\hat{P}_{y,a'} = \sum_a \left(\frac{\hat{C}_{y,a}}{\sum_a \hat{C}_{y,a}} \right) * T_{a,a'}$$ Fishery age composition
Proportion at age

$$\hat{P}_{y,l} = \sum_a \left(\frac{\hat{C}_{y,a}}{\sum_a \hat{C}_{y,a}} \right) * T_{a,l}$$ Fishery length composition
Proportion at length

Equations describing population dynamics

Start year

$$N_a = \begin{cases} e^{\left(\mu_r + \tau_{styr - a_0 - a - 1}\right)}, & a = a_0 \\ e^{\left(\mu_r + \tau_{styr - a_0 - a - 1}\right)} e^{-(a - a_0)M}, & a_0 < a < a_+ \\ \dfrac{e^{\left(\mu_r\right)} e^{-(a - a_0)M}}{\left(1 - e^{-M}\right)}, & a = a_+ \end{cases}$$

Number at age of recruitment

Number at ages between recruitment and pooled age class

Number in pooled age class

Subsequent years

$$N_{y,a} = \begin{cases} e^{\left(\mu_r + \tau_y\right)}, & a = a_0 \\ N_{y-1,a-1} * e^{-Z_{y-1,a-1}}, & a_0 < a < a_+ \\ N_{y-1,a-1} * e^{-Z_{y-1,a-1}} + N_{y-1,a} * e^{-Z_{y-1,a}}, & a = a_+ \end{cases}$$

Number at age of recruitment

Number at ages between recruitment and pooled age class

Number in pooled age class

Formulae for likelihood components **BOX 1 (Continued)**

$L_1 = \lambda_1 \sum_y \left(\ln \left[\frac{C_y + 0.01}{\hat{C}_y + 0.01} \right] \right)^2$	Catch likelihood
$L_2 = \lambda_2 \sum_y \frac{\left(I_y - \hat{I}_y\right)^2}{2 * \hat{\sigma}^2 \left(I_y\right)}$	Survey biomass index likelihood
$L_3 = \lambda_3 \sum_{styr}^{endyr} -n^*{}_y \sum_a^{a+} \left(P_{y,a} + 0.001\right) * \ln\left(\hat{P}_{y,a} + 0.001\right)$	Fishery age composition likelihood
$L_4 = \lambda_4 \sum_{styr}^{endyr} -n^*{}_y \sum_l^{l+} \left(P_{y,l} + 0.001\right) * \ln\left(\hat{P}_{y,l} + 0.001\right)$	Fishery length composition likelihood
$L_5 = \lambda_5 \sum_{styr}^{endyr} -n^*{}_y \sum_a^{a+} \left(P_{y,a} + 0.001\right) * \ln\left(\hat{P}_{y,a} + 0.001\right)$	Survey age composition likelihood
$L_6 = \lambda_6 \sum_{styr}^{endyr} -n^*{}_y \sum_l^{l+} \left(P_{y,l} + 0.001\right) * \ln\left(\hat{P}_{y,l} + 0.001\right)$	Survey size composition likelihood
$L_7 = \frac{1}{2\sigma_q^2} \left(\ln \, q / q_{prior} \right)^2$	Penalty on deviation from prior distribution of catchability coefficient
$L_8 = \frac{1}{2\sigma_{\sigma_r}^2} \left(\ln \sigma_r / \sigma_{r(prior)} \right)^2$	Penalty on deviation from prior distribution of recruitment deviations
$L_9 = \lambda_9 \left[\frac{1}{2 * \sigma_r^2} \sum_y \tau_y^2 + n_y * \ln\left(\sigma_r\right) \right]$	Penalty on recruitment deviations
$L_{10} = \lambda_{10} \sum_y \phi_y^2$	Fishing mortality regularity penalty
$L_{11} = \lambda_{11} \bar{s}^2$	Average selectivity penalty (attempts to keep average selectivity near 1)
$L_{12} = \lambda_{12} \sum_{a_0}^{a_+} \left(s_i - s_{i+1}\right)^2$	Selectivity dome-shaped penalty – only penalizes when the next age's selectivity is lower than the previous (penalizes a downward selectivity curve at older ages)
$L_{13} = \lambda_{13} \sum_{a_0}^{a_+} \left(FD(FD(s_i - s_{i+1})\right)^2$	Selectivity regularity penalty (penalizes large deviations from adjacent selectivity by adding the square of second differences)
$L_{total} = \sum_{i=1}^{13} L_i$	Total objective function value

Description of Alternative Models

A suite of incremental models were run to investigate the effects of removing 1980s survey data from the assessment, increasing the length plus group, re-weighting of compositional data, and changing the survey biomass weight from 0.25 to 1.0.

The models examined are:

Model	Description
base	2020 model (m18.2b) and results (includes 1980s survey data)
m18.2b	base model w/data updated through 2022
m22	m18.2b using GAP default VAST (survey data 1990+)
m22.1	m22 w/increased length plus group
m22.1a	m22.1 re-weighted
m22.1b	m22.1 re-weighted, with survey weight = 1

Since the SSC and Plan Team have both recommended that 1980s survey data be excluded for GOA assessments. The base model and m18.2b are presented for comparison but are not discussed. Going forward m22 will be considered the base model as it excludes the 1980s survey data. Three additional variants of m22 were examined to explore the effects of increasing the length composition plus group by 5 cm (m22.1), re-weighting age and length compositional data (m22.1a), and re-weighting with the survey weight changed to 1.0 (m22.1b). The trawl survey weighting was set at 0.25 (the equivalent of doubling the survey variance) for the past two full assessment cycles in order to reduce the influence of the highly precise VAST survey abundance estimates.

Parameters Estimated Outside the Assessment Model

A von Bertalanffy growth curve was fitted, for both sexes combined, to survey size at age data from 1990-2021 using length-stratified methods (Quinn and Deriso 1999; Bettoli and Miranda 2001). An age to size conversion matrix was then constructed by adding normal error with a standard deviation equal to the survey data for the probability of different sizes for each age class. The length-weight relationship for combined sexes, using the formula $W = aL^b$, where W is weight in grams and L is fork length in mm, a = 0.0783 and b = 2.0742. Previous parameters are available from Heifetz and Clausen (1991); Courtney *et al.* (1999); and Malecha *et al.* (2007). The estimated parameters for the growth curve from length-stratified methods are:
L_∞ = 41.68 cm, κ = 0.16, and t_0 = -0.38.

Weight-at-age was constructed with weight at age data from the same data set as the length at age. Mean weight-at-age is approximated by the equation:

$$W_a = W_\infty\left(1 - e^{\left(-\kappa(age-t_0)\right)}\right)^b.$$

The estimated growth parameters from length-stratified methods are:
W_∞ = 1081 g, κ = 0.17, t_0 = -0.16, and b = 3.04.

Aging error matrices were constructed by assuming that the break-and-burn ages were unbiased but had a given amount of normal error around each age based on between-reader percent agreement tests conducted at the AFSC Age and Growth lab. We fix the variability of recruitment deviations (σ_r) at 1.5 which allows for highly variable recruitment.

Parameters Estimated Inside the Assessment Model

The estimates of natural mortality (*M*) and catchability (*q*) are computed with the use of lognormal prior distributions as penalties that are added to the overall objective function in order to constrain parameter estimates to reasonable values and to speed model convergence. Arithmetic means and standard errors (μ, σ) for the lognormal distributions were provided as inputs to the model. The standard errors for selected model parameters were estimated based on multivariate normal approximation of the covariance matrix. The prior mean for natural mortality of 0.06 is based on the estimate provided by Heifetz and Clausen (1991) using the methods of Alverson and Carney (1975). Natural mortality is a difficult parameter to estimate within the model so we assign a "tight" prior CV of 5%. Catchability is a parameter that is unclear for rockfish, so while we assign it a prior mean of 1 (assuming all fish in the area swept are captured and there is no herding of fish from outside the area swept, and that there is no effect of untrawlable grounds), we assign it a less precise CV of 45%. This allows the parameter more freedom than that allowed to natural mortality. These methods are also used in the GOA Pacific ocean perch and GOA dusky rockfish assessments.

The fit to the combined observations of maturity-at-age obtained in the preferred assessment model is shown in Figure 10-8. Parameters for the logistic function describing maturity-at-age estimated conditionally in the model, as well as all other parameters estimated conditionally, were identical to estimating maturity-at-age independently. Estimating maturity-at-age parameters conditionally influences the model only through the evaluation of uncertainty, as the MCMC procedure includes variability in the maturity parameters in conjunction with variability in all other parameters, rather than assuming the maturity parameters are fixed. Thus, estimation of maturity-at-age within the assessment model allows for uncertainty in maturation to be incorporated into uncertainty for key model results (e.g., ABC).

Given that we are using Bayesian estimation, there is no need to implement a recruitment bias-correction algorithm (e.g., Methot and Taylor 2011).

The numbers of estimated parameters from the model are:

Parameter	Symbol	Number
Natural mortality	M	1
Catchability	q	1
Log mean recruitment	μ_r	1
Spawners per recruit levels	$F_{35\%}, F_{40\%}, F_{50\%}$	3
Recruitment deviations	τ_y	110
Average fishing mortality	μ_F	1
Fishing mortality deviations	ϕ_y	62
Logistic fishery selectivity	$a_{f50\%}, \gamma_f$	2
Logistic survey selectivity	$a_{s50\%}, \gamma_s$	2
Logistic maturity at age	$a_{m50\%}, \gamma_m$	2
Total		185

Evaluation of model uncertainty is obtained through a Markov Chain Monte Carlo (MCMC) algorithm (Gelman *et al.* 1995). The chain length of the MCMC was 10,000,000 and was thinned to one iteration out of every 2,000. We omit the first 1,000,000 iterations to allow for a burn-in period. We use these MCMC methods to provide further evaluation of uncertainty in the results below including 95% credible intervals for some parameters (computed as the 5^{th} and 95^{th} percentiles of the MCMC samples).

Results

Model Evaluation

The author's preferred model is model m22.1. The examined models were:

Model	Description
base	2020 model (m18.2b) and results (includes 1980s survey data)
m18.2b	base model w/data updated through 2022
m22	m18.2b using GAP default VAST (survey data 1990+)

Model	Description
m22.1	m22 w/increased length plus group
m22.1a	m22.1 re-weighted
m22.1b	m22.1 re-weighted, with survey weight = 1

When we present alternative model configurations, our usual criteria for choosing a superior model are: (1) the best overall fit to the data (in terms of negative log-likelihood), (2) biologically reasonable patterns of estimated recruitment, catchabilities, and selectivity, (3) a good visual fit to length and age compositions, and (4) parsimony. We've presented results for multiple models because the 2020 and 2022 models differ in either trawl survey biomass inputs, the length plus group was increased, or the model was re-weighted iteratively. The 'base' model and m18.2b are excluded from consideration since they use trawl survey data from the 1980s. A general examination of these models relative to m22 shows an increase in estimate trawl survey biomass when 2021 survey data is included and a further increase in estimated biomass when the 1980s data are excluded (Figure 10-10). However m18.2b and m22 generate essentially the same total and spawning biomass (Figure 10-11) though m22 has a lower data likelihood (Table 10-13). Survey biomass estimates are very similar between models m22, m22.1, and m22.1a (Figure 10-12) with only m22.1b presenting a different assessment output with lower estimates of biomass in early years and a higher estimates of survey biomass in later years.
However, the total and spawning biomass estimates from models m22, m22.1, and m22.1a do differ (Figure 10-13). Increasing the length composition plus size by 5cm slightly decreases abundance and re-weighting this model further decreases abundance. The iterative re-weighting process used in m22.1a changed the fishery age composition, survey age composition, and fishery length composition weights (previously all set at 0.5) to 1.339, 0.835 and 0.973, respectively. This model increases the data likelihood (Table 10-13), though the re-weighted model is not directly comparable to m 22 or m22.1. Of note is the increase in catchability *q* which has the effect of reducing abundance. Model m22.1b is the only model that changes biomass other than simply by scale, which is a response to the change in compositional data weightings and survey weight. Overall compositional data weights were similar to those from m22.1a at 1.325, 0.827, and 0.984 for the fishery age, survey age, and survey length compositional data weights, respectively. Model m22.1b again increases the data likelihood, though is not directly comparable to the other models due to the re-weighting, it also has the highest estimated biomass and ABC.

Model m22.1 produces good visual fits to the data, and biologically reasonable patterns of recruitment, abundance, and selectivity. Therefore, the recommended 2022 model is utilizing the new information effectively, and we use it to recommend the 2023 ABC and OFL. While the re-weighted models are compelling, particularly to change the survey biomass weight to 1.0, there appears to be a wide range of outcomes from small changes in data weights and we would prefer to explore this more before putting forward one of these models to provide advice for management.

Time Series Results

Key results have been summarized in Tables 10-13 – 10-16. In general, model predictions continue to fit the data well (Figures 10-1 – 10-4, 10-6)

Definitions
Spawning biomass is the biomass estimate of mature females in tons. Total biomass is the biomass estimate of all northern rockfish age-2 and greater in tons. Recruitment is measured as number of age-2 northern rockfish. Fishing mortality is fully-selected *F*, meaning the mortality at the age the fishery has fully selected the fish.

Biomass and Exploitation Trends
The estimates of current population abundance indicate that it is dominated by fish from the 1993 and 1998 year-classes (Table 10-14). Since the early 1990s the total biomass estimated in the model plateaued

close to 200,000 t through the early 2000s and has been decreasing since (Figure 10-14). Similarly, the spawning biomass estimated in the model has also been decreasing since the mid 2000s. From 1990 on total biomass is generally folling the trend observed in the fit to VAST model-based survey biomass index (Figure 10-4).

The estimated selectivity curve for the fishery and survey data suggested a pattern similar to previous assessments for northern rockfish (Figure 10-8). The commercial fishery targets slightly larger and (likely) older fish and the survey should sample a larger range of ages. Ninety-five percent of northern rockfish are selected in the fishery by age 10. The age at 50% selection is 9.1 for the survey and 8.2 for the fishery, age at 50% maturity is estimated at 10.6 years.

Goodman *et al.* (2002) suggested that stock assessment authors use a "management path" graph as a way to evaluate management and assessment performance over time. In the management path we plot the ratio of fishing mortality to F_{OFL} ($F_{35\%}$) and the estimated spawning biomass relative to $B_{35\%}$. Harvest control rules based on $F_{35\%}$ and $F_{40\%}$ and the tier 3b adjustment are provided for reference. The historical management path for northern rockfish has been above the F_{OFL} adjusted limit for only a few years in the 1960s. In recent years, northern rockfish have been above $B_{35\%}$ and below $F_{35\%}$ (Figure 10-15). The trajectory of fishing mortality has remained below the $F_{40\%}$ level most of the time and below $F_{35\%}$ in all years except 1964-76 during the period of intense fishing for Pacific ocean perch. Parameter estimates from this year's model were similar to the previous northern rockfish assessment (Table 10-13). Selectivity estimates for the fishery and the survey are similar, but with the survey selectivity increasing somewhat more gradually with age. Compared to the maturity at age curve that is estimated, selectivity occurs at slightly younger ages than the age of maturity (Table 10-14 and Figure 10-8). The fishing mortality rate *F* has been fairly consistent since 1990 (Figure 10-16), and the exploitation rate has been generally around the long-term average (Figure 10-17).

Recruitment

Recruitment estimates show a high degree of uncertainty, but indicate several large year-classes in the early and late 1970's, early 1980's and mid 1990's (Tables 10-15 and 10-16 and Figure 10-18). Recruitment since 2005 has been considerably lower than the 1970–2005 time period. There is no clear trend between recruitment and spawning stock biomass (Figure 10-9). Fits to the fishery and survey age compositions were reasonable with this year's recommended model (Figures 10-3 and 10-6). Increasing proportions of GOA northern rockfish in the plus age or length groups for both survey and fishery composition indicate a substantial number of individuals are successfully surviving natural and fishing mortality to attain old age and large size.

Retrospective analysis

From the MCMC chains described in the *Uncertainty approach* section, we summarize the posterior densities of key parameters for the recommended model using histograms (Figure 10-19) and credible intervals (Table 10-17). We also use these posterior distributions to show uncertainty around time series estimates such as total biomass, recruitment, and spawning biomass (Figures 10-14, 10-18, 10-20).

Table 10-17 shows the maximum likelihood estimate (MLE) of key parameters with their corresponding standard deviations derived from the Hessian matrix compared to the standard deviations derived from MCMC methods. The Hessian and MCMC standard deviations are larger for the estimates of q, $F_{40\%}$, ABC, and female spawning biomass. These larger standard deviations indicate that these parameters are more uncertain than indicated by the standard estimates. However, all estimates fall within the Bayesian credible intervals. The distributions of these parameters are slightly skewed with higher MLE estimates than MCMC medians for current spawning and total biomass and ABC, indicating possibilities of higher biomass estimates (Figure 10-19). Uncertainty estimates in the time series of spawning biomass also result in a skewed distribution towards higher values, particularly at the end of the time series and into the 15 year projected times series (Figure 10-20).

A within-model retrospective analysis of the recommended model was conducted for the last 10 years of the time-series by dropping data one year at a time. The revised Mohn's "rho" statistic (Hanselman *et al.* 2013) in female spawning biomass was -0.082, an improvement from -0.236 in the previous model) indicating that the model slightly increases the estimate of female spawning biomass in recent years as data is added to the assessment. The retrospective female spawning biomass and the relative difference in female spawning biomass from the model in the terminal year are shown in Figure 10-21 (with 95% credible intervals from MCMC).

Harvest recommendations

Amendment 56 Reference Points

Amendment 56 to the GOA Groundfish Fishery Management Plan defines the "overfishing level" (OFL), the fishing mortality rate used to set OFL (F_{OFL}), the maximum permissible ABC, and the fishing mortality rate used to set the maximum permissible ABC. The fishing mortality rate used to set ABC (F_{ABC}) may be less than this maximum permissible level, but not greater. Because reliable estimates of reference points related to maximum sustainable yield (MSY) are currently not available but reliable estimates of reference points related to spawning per recruit are available, Northern rockfish in the GOA are managed under Tier 3 of Amendment 56. Tier 3 uses the following reference points: $B_{40\%}$, equal to 40% of the equilibrium spawning biomass that would be obtained in the absence of fishing; $F_{35\%}$,,equal to the fishing mortality rate that reduces the equilibrium level of spawning per recruit to 35% of the level that would be obtained in the absence of fishing; and $F_{40\%}$, equal to the fishing mortality rate that reduces the equilibrium level of spawning per recruit to 40% of the level that would be obtained in the absence of fishing. Estimation of the $B_{40\%}$ reference point requires an assumption regarding the equilibrium level of recruitment. In this assessment, it is assumed that the equilibrium level of recruitment is equal to the average of age-2 recruitments between 1979 and 2020. Because of uncertainty in very recent recruitment estimates, we lag 2 years behind model estimates in our projection. Other useful biomass reference points which can be calculated using this assumption are $B_{100\%}$ and $B_{35\%}$, defined analogously to $B_{40\%}$. The 2022 estimates of these reference points are:

$B_{100\%}$	$B_{40\%}$	$B_{35\%}$	$F_{40\%}$	$F_{35\%}$
82,350	32,940	28,822	0.074	0.061

Specification of OFL and Maximum Permissible ABC

Female spawning biomass for 2022 is estimated at 39,445 t. This is above the $B_{40\%}$ value of 32,940 t. Under Amendment 56, Tier 3, the maximum permissible fishing mortality for ABC is $F_{40\%}$ and fishing mortality for OFL is $F_{35\%}$. Applying these fishing mortality rates for 2022, yields the following ABC and OFL:

ABC	OFL
4,965	5,927

A standard set of projections is required for each stock managed under Tiers 1, 2, or 3 of Amendment 56. This set of projections encompasses seven harvest scenarios designed to satisfy the requirements of Amendment 56, the National Environmental Policy Act, and the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA).

For each scenario, the projections begin with the vector of 2022 numbers at age as estimated in the assessment. This vector is then projected forward to the beginning of 2023 using the schedules of natural mortality and selectivity described in the assessment and the best available estimate of total (year-end) catch for 2022. In each subsequent year, the fishing mortality rate is prescribed on the basis of the spawning biomass in that year and the respective harvest scenario. In each year, recruitment is drawn from an inverse Gaussian distribution whose parameters consist of maximum likelihood estimates determined from recruitments estimated in the assessment. Spawning biomass is computed in each year based on the time of peak spawning and the maturity and weight schedules described in the assessment. Total catch after 2022 is assumed to equal the catch associated with the respective harvest scenario in all years. This projection scheme is run 1,000 times to obtain distributions of possible future stock sizes, fishing mortality rates, and catches.

Five of the seven standard scenarios will be used in an Environmental Assessment prepared in conjunction with the final SAFE. These five scenarios, which are designed to provide a range of harvest alternatives that are likely to bracket the final TAC for 2023, are as follow ("$maxF_{ABC}$" refers to the maximum permissible value of F_{ABC} under Amendment 56):

- Scenario 1: In all future years, *F* is set equal to $maxF_{ABC}$. (Rationale: Historically, TAC has been constrained by ABC, so this scenario provides a likely upper limit on future TACs.)
- Scenario 2: In 2022 and 2023, *F* is set equal to a constant fraction of $maxF_{ABC}$, where this fraction is equal to the ratio of the realized catches in 2019-2021 to the ABC recommended in the assessment for each of those years. For the remainder of the future years, maximum permissible ABC is used. (Rationale: In many fisheries the ABC is routinely not fully utilized, so assuming an average ratio catch to ABC will yield more realistic projections.)
- Scenario 3: In all future years, *F* is set equal to 50% of $maxF_{ABC}$. (Rationale: This scenario provides a likely lower bound on F_{ABC} that still allows future harvest rates to be adjusted downward when stocks fall below reference levels.)
- Scenario 4: In all future years, *F* is set equal to the 2017-2021 average *F*. (Rationale: For some stocks, TAC can be well below ABC, and recent average *F* may provide a better indicator of F_{TAC} than F_{ABC}.)
- Scenario 5: In all future years, *F* is set equal to zero. (Rationale: In extreme cases, TAC may be set at a level close to zero.)

Two other scenarios are needed to satisfy the MSFCMA's requirement to determine whether a stock is currently in an overfished condition or is approaching an overfished condition. These two scenarios are as follows (for Tier 3 stocks, the MSY level is defined as $B_{35\%}$):

- Scenario 6: In all future years, *F* is set equal to F_{OFL}. (Rationale: This scenario determines whether a stock is overfished. If the stock is expected to be 1) above its MSY level in 2022 or 2) above ½ of its MSY level in 2022 and above its MSY level in 2032 under this scenario, then the stock is not overfished.)
- Scenario 7: In 2023 and 2024, *F* is set equal to max F_{ABC}, and in all subsequent years F is set equal to FOFL. (Rationale: This scenario determines whether a stock is approaching an overfished condition. If the stock is 1) above its MSY level in 2024 or 2) above 1/2 of its MSY level in 2024 and expected to be above its MSY level in 2034 under this scenario, then the stock is not approaching an overfished condition.)

Spawning biomass, fishing mortality, and yield are tabulated for the seven standard projection scenarios (Table 10-18). For projections in Scenario 2 (Author's *F*); we use pre-specified catches to increase accuracy of short-term projections in fisheries where the catch is usually less than the ABC. This was suggested to help management with setting preliminary ABCs and OFLs for two-year ahead specifications.

In addition to the seven standard harvest scenarios, Amendments 48/48 to the BSAI and GOA Groundfish Fishery Management Plans require projections of the likely OFL two years into the future. While Scenario 6 gives the best estimate of OFL for 2022, it does not provide the best estimate of OFL for 2023, because the mean 2022 catch under Scenario 6 is predicated on the 2022 catch being equal to the 2022 OFL, whereas the actual 2022 catch will likely be less than the 2022 OFL. The executive summary contains the appropriate one- and two-year ahead projections for both ABC and OFL.

Risk Table and ABC recommendation

The SSC in its December 2018 minutes recommended that all assessment authors use the risk table when determining whether to recommend an ABC lower than the maximum permissible. The following template is used to complete the risk table:

	Assessment-related considerations	***Population dynamics considerations***	***Environmental/ecosystem considerations***	***Fishery Performance***
Level 1: Normal	Typical to moderately increased uncertainty/minor unresolved issues in assessment.	Stock trends are typical for the stock; recent recruitment is within normal range.	No apparent environmental/ecosystem concerns	No apparent fishery/resource-use performance and/or behavior concerns
Level 2: Substantially increased concerns	Substantially increased assessment uncertainty/ unresolved issues.	Stock trends are unusual; abundance increasing or decreasing faster than has been seen recently, or recruitment pattern is atypical.	Some indicators showing adverse signals relevant to the stock but the pattern is not consistent across all indicators.	Some indicators showing adverse signals but the pattern is not consistent across all indicators
Level 3: Major Concern	Major problems with the stock assessment; very poor fits to data; high level of uncertainty; strong retrospective bias.	Stock trends are highly unusual; very rapid changes in stock abundance, or highly atypical recruitment patterns.	Multiple indicators showing consistent adverse signals a) across the same trophic level as the stock, and/or b) up or down trophic levels (i.e., predators and prey of the stock)	Multiple indicators showing consistent adverse signals a) across different sectors, and/or b) different gear types
Level 4: Extreme concern	Severe problems with the stock assessment; severe retrospective bias. Assessment considered unreliable.	Stock trends are unprecedented; More rapid changes in stock abundance than have ever been seen previously, or a very long stretch of poor recruitment compared to previous patterns.	Extreme anomalies in multiple ecosystem indicators that are highly likely to impact the stock; Potential for cascading effects on other ecosystem components	Extreme anomalies in multiple performance indicators that are highly likely to impact the stock

The table is applied by evaluating the severity of four types of considerations that could be used to support a scientific recommendation to reduce the ABC from the maximum permissible. These considerations are stock assessment considerations, population dynamics considerations, environmental/ecosystem considerations, and fishery performance. Examples of the types of concerns that might be relevant include the following:

1. “Assessment considerations—data-inputs: biased ages, skipped surveys, lack of fishery-independent trend data; model fits: poor fits to fits to fishery or survey data, inability to

simultaneously fit multiple data inputs; model performance: poor model convergence, multiple minima in the likelihood surface, parameters hitting bounds; estimation uncertainty: poorly-estimated but influential year classes; retrospective bias in biomass estimates.

2. "Population dynamics considerations—decreasing biomass trend, poor recent recruitment, inability of the stock to rebuild, abrupt increase or decrease in stock abundance.
3. "Environmental/ecosystem considerations—adverse trends in environmental/ecosystem indicators, ecosystem model results, decreases in ecosystem productivity, decreases in prey abundance or availability, increases or increases in predator abundance or productivity.
4. "Fishery performance—fishery CPUE is showing a contrasting pattern from the stock biomass trend, unusual spatial pattern of fishing, changes in the percent of TAC taken, changes in the duration of fishery openings."

Assessment considerations

Level 1. In recent assessments the GOA northern rockfish assessment model has resulted in a negative retrospective pattern, which is interpreted as the model continually increases spawning biomass as new data are added (-0.20 in 2018, -0.24 in 2020, and -0.082 in the current assessment, Figure 10-21). While the assessment fits to composition data from the survey (age) and fishery (age) are generally adequate (Figures 10-3 and 10-6), the fishery length compositions (Figure 10-2) are misaligned, though this fit has improved with the increase in the length plus group size. Changing from a design-based model to a VAST-based estimate has made the survey biomass estimates more realistic (less overall fluctuation) though the model continues to fit these data poorly. There is some question as to the efficacy of this trawl survey for developing indices of northern rockfish abundance. The items described here have been an issue for assessing northern rockfish for some time, we scored this category as Level 1, as the level of concern has not changed.

Population dynamics considerations

Level 2. Recruitment since 2005 has been considerably lower than in 1970–2005. There is increasing proportions of GOA northern rockfish in the plus age groups for both survey and fishery age composition that indicates a substantial number of individuals are successfully surviving natural and fishing mortality to attain older ages and larger sizes. There is a reduction in body condition in recent years for young rockfish, though how this propagates through time is unclear. Skip spawning has been observed for this species, the spatial and temporal extent which is unknown. However, preliminary investigations that incorporate skip spawning in maturity estimates lead to a reduction is spawning biomass and associated ABC.
For these reasons we have given this risk table factor a level 2 concern for population dynamics considerations though make no recommendation for a reduction in ABC.

Environmental/Ecosystem considerations

Level 1. Environmental mechanisms for changes in survival remain unknown, though changes in water temperature and currents could have effects on prey abundance and success of transition of rockfish from pelagic to demersal stage. Predator effects would likely be more important on larval, post-larval, and small juvenile slope rockfish, but there is insufficient information on these life stages and their predators to inform a conclusion. Additionally, changes in bottom habitat due to natural or anthropogenic causes could alter survival rates by altering available shelter, prey, or other functions. Estimates of structural epifauna habitat (estimated using non-targeted data) have recently been in decline. However, given the continued lack of biological and habitat information for northern rockfish, we scored this category as Level 1, as the level of concern has not changed.

Fishery performance

Level 1. Fishers usually direct their efforts first toward Pacific ocean perch because of its higher value relative to northern rockfish. After the TAC for Pacific ocean perch has been reached and NMFS closes directed fishing for this species, trawlers switch and target northern rockfish. The directed GOA northern rockfish fishery is concentrated on a limited number of highly productive locations. The patterns of fishing and percent of TAC taken have not substantially changed in the last three years, therefore we scored this category as Level 1.

Summary and ABC recommendation

Assessment-related considerations	*Population dynamics considerations*	*Environmental/ecosystem considerations*	*Fishery Performance*
Level 1: No increased concerns	Level 2: Substantially increased concerns	Level 1: No increased concerns	Level 1: No increased concerns

We have ranked three categories as ‘Level 1: No apparent concern’ and one as a ‘Level 2, substantially increased concerns’. The GOA northerm rockfish assessment appears to fit available data well, the 2021 GOA trawl survey was undertaken as planned and data are included in this year’s assessment, and the fishery and environmental considerations appear to be within normal bounds. Because GOA northern rockfish ABC is has not been fully utilized in recent years we are not recommending a reduction in ABC at this time. We anticipate that we will monitor the survey abundance estimates, catch rates, and explore skip spawning more fully in the next assessment.

Area Allocation of Harvests

Apportionment of ABC and OFL among regulatory areas has been based on the random effects model developed by the survey averaging working group. The random effects model was fit to the survey biomass estimates (with associated variance) for the Western, Central, and Eastern GOA. The random effects model estimates a process error parameter (constraining the variability of the modeled estimates among years) and random effects parameters in each year modeled. The fit of the random effects model to survey biomass in each area is shown in Figure 10-22.

In general the random effects model fits the area-specific design-based survey biomass estimates reasonably well. Based on the random effects estimates the area apportionments for GOA northern rockfish are 52.7% for the Western area (up from 37.76% in 2021), 47.3% for the Central area (down from 62.22% in 2018), and 0.02% for the Eastern area (same as 2021). The changes are due to the more frequent catches of northern rockfih in the western GOA during the 2021 survey Figure 10-5. Applying the random effect model apportionments to the recommended ABC for northern rockfish results in 2,614 t for the Western area, 2,350 t for the Central area, and 1 t for the Eastern area for 2023. For management purposes, the small ABC of northern rockfish in the Eastern area is combined with the Other Rockfish complex.

Status Determination

Under the MSFCMA, the Secretary of Commerce is required to report on the status of each U.S. fishery with respect to overfishing. This report involves the answers to three questions: 1) Is the stock being subjected to overfishing? 2) Is the stock currently overfished? 3) Is the stock approaching an overfished condition?

Is the stock being subjected to overfishing? The official catch estimate for the most recent complete year (2021) is 2,376 t. This is less than the 2021 OFL of 0 t. Therefore, the stock is not being subjected to overfishing.

Harvest Scenarios #6 and #7 are intended to permit determination of the status of a stock with respect to its minimum stock size threshold (MSST). Any stock that is below its MSST is defined to be overfished. Any stock that is expected to fall below its MSST in the next two years is defined to be approaching an overfished condition. Harvest Scenarios #6 and #7 are used in these determinations as follows:

Is the stock currently overfished? This depends on the stock's estimated spawning biomass in 2022:

a. If spawning biomass for 2022 is estimated to be below ½ $B_{35\%}$, the stock is below its MSST.

b. If spawning biomass for 2022 is estimated to be above $B_{35\%}$ the stock is above its MSST.

c. If spawning biomass for 2022 is estimated to be above ½ $B_{35\%}$ but below $B_{35\%}$, the stock's status relative to MSST is determined by referring to harvest Scenario #6 (Table 10-18).

If the mean spawning biomass for 2034 is below $B_{35\%}$, the stock is below its MSST. Otherwise, the stock is above its MSST.

Is the stock approaching an overfished condition? This is determined by referring to harvest Scenario #7:

a. If the mean spawning biomass for 2024 is below 1/2 $B_{35\%}$, the stock is approaching an overfished condition.

b. If the mean spawning biomass for 2024 is above $B_{35\%}$, the stock is not approaching an overfished condition.

c. If the mean spawning biomass for 2024 is above 1/2 $B_{35\%}$ but below $B_{35\%}$, the determination depends on the mean spawning biomass for 2034 If the mean spawning biomass for 2034 is below $B_{35\%}$, the stock is approaching an overfished condition. Otherwise, the stock is not approaching an overfished condition.

Based on the above criteria and Table 10-18, the stock is not overfished and is not approaching an overfished condition. The fishing mortality that would have produced a catch for last year equal to last year's OFL is 0.0763.

Ecosystem Considerations

In general, a determination of ecosystem considerations for GOA northern rockfish is hampered by a lack of biological and habitat information. However, a review of the most recent (2021) GOA Ecosystem Status Report did not reveal strong evidence of declining trends in indicators which results in strong concern for northern rockfish. Information regarding the FMP, non-FMP, and prohibited species caught in rockfish target fisheries to help understand ecosystem impacts by the northern fishery (Tables 12-2 - 12-4).

Ecosystem Effects on the Stock

Prey availability/abundance trends: Unfortunately, there is no information on the food habits of larval or post-larval rockfish to help determine possible relationships between prey availability and year-class strength. Moreover, identification to the species level for field collected larval slope rockfish is difficult. Visual identification is not possible, though genetic techniques allow identification to species level for larval slope rockfish. Some juvenile rockfish found in inshore habitat feed on shrimp, amphipods, and other crustaceans, as well as some mollusk and fish. Adult northern rockfish feed on euphausiids. Euphausiids are also a major item in the diet of walleye pollock. Changes in the abundance of walleye pollock could lead to a corollary change in the availability of euphausiids, which could then impact northern rockfish. Northern rockfish body condition in 2021 improved from 2019, but continued to be below average, a persistent trend since 2013. Limited information on biomass of calanoid copepod and euhausiids (adult prey) in 2022 indicate average to above average availability (Drummond and Renner 2022; Fergusson 2022; Hatch and Piatt 2022; Hopcroft 2022). Shrimp (juvenile prey) CPUEs have been increasing in the Chirikof, Yakutat, and Southeastern regions over 2019 and 2021 AFSC bottom trawl surveys, while they have declined in the Kodiak region (Palsson 2021a). We have no information on other juvenile prey species, such as myctophids, squids, hermit crabs, and molluscs.

Predator population trends: There is no indication of increased predation or competition on northern rockfish. Potential predators include Pacific halibut and other large fish. Competitors for zooplankton prey could include Pacific Ocean perch (Hulson *et al.* 2021), which remains in high abundance, and walleye pollock, which slightly declined in 2022 (Monnahan *et al.* 2021). Predator effects would likely be more important on larval, post-larval, and small juvenile northern rockfish, but information on these life stages and their predators is lacking. However, survival of larvae are thought to be more related to the abundance and timing of prey availability than predation, due to the lack of rockfish as a prey item commonly found in diets.

Changes in physical environment: Changes in structural habitat present a potential concern for northern rockfish. Vertical structure, including sponges, corals, and rocky habitat, is important habitat for northern rockfish and has experienced multi-year decline (with high uncertainty) across the GOA. Observations in 2021 from AFSC's bottom trawl and observer data of non-target catches (both not designed to sample structural epifauna and associated with high uncertainty) can be used to monitor trends in structural epifauna, although with uncertainty as these surveys/fisheries are not designed to target these species Whitehouse and Gaichas (2021).
By combining this fishery independent (AFSC survey) and fishery dependent (observer data) datasets, however, we can see a consistent trend rise above potential variability due to potential gear and effort changes (observer data) and the non-targeted sampling of both methods. A VAST model was run for gorgonian corals, pennatulaceans (e.g., sea pens), and sponges integrating and modeling trawls station densities across the GOA (Palsson 2021). The coral abundance index is variable over time but the trend suggests low abundances resulting from the two most recent surveys (2019 and 2021) compared to most index values observed before 2017. The gulf-wide abundance of pennatulaceans shows an increasing trend from 1990 to 2005 and then a variable trend thereafter and a peak in 2017 followed by a decline in 2019. However, the 2021 index value increased from the 2019 value. The trend of sponges shows relative stability until 2015 followed by a continual 7 year decline in the GOA wide index through 2021 to a historic low value. The declines in sponges are driven by trends in western GOA. Sea anemones (not modeled in VAST) declined in Shumangins in 2019 and 2021, and Kodiak experienced a slight decline in 2021.

It is reasonable to expect that the 2022, and predicted 2023 average deeper ocean temperatures, would provide moderate spawning habitat and surface thermal conditions for northern rockfish during a time when they are spawning and growing to a size that promotes over winter survival. Larval abundance of northern rock sole, along with late winter/early spring shelf spawners (e.g., Pacific cod and walleye pollock), associate with cooler winters and enhanced alongshore spring winds. Larval surveys in Shelikof Strait in 2021 observed approximately average abundance of larval rockfish (not identified to species) and age-0 surveys in western GOA (2022) observed above average Pacific cod and walleye pollock larval abundance indicating moderate to above average conditions for northern rock sole. Surface temperatures were below average in the winter, transitioned from below average to above average in the spring Fergusson (2022), and above average in the summer across the GOA (Seward Line: 12.3°C). Thermal conditions for adults (banks along shelf edge approximately 75-150m) may have slightly increased to above average in 2022 (longline survey (250m), Siwicke 2022). AFSC bottom trawl survey data revealed a western shift and slight decrease in depth in northern rockfish distribution within the GOA with no relationship to change in temperature.

Euphausiids are also a major item in the diet of walleye pollock. Changes in the abundance of walleye pollock could lead to a corollary change in the availability of euphausiids, which could then impact northern rockfish. The limited information available on temperature and zooplankton indicate average foraging and growing conditions for the zooplanktivorous northern rockfish during 2020. Heat wave conditions occurred during 2020 but were not as severe as 2019 during the summer and fall in the GOA (Barbeaux 2020). Sea surface temperatures were about 1°C above normal in the western GOA and average in the eastern GOA during the 2020 summer (Alaska Center for Climate Assessment & Policy ACCAP, Thoman personal communication). Inside waters of the GOA were slightly more anomalously warm than offshore temperatures (ACCAP). Offshore of Kodiak, waters above the continental shelf along the GAK line remained anomalously warm (0.5°C) at 200-250 m depth in 2020 but cooler than 2019 (Danielson *et al.* 2020). Along the GOA slope, the AFSC Longline Survey Subsurface Temperature Index indicates above average temperatures at the surface and at depth (250 m) in 2020 relative to the 2005-2019 time series and cooler temperatures in 2020 relative to 2019 (Siwicke personal communication). In the inside waters, Prince William Sound has remained warm since 2014 (Danielson *et al.* 2020). However, for the inside waters of the eastern GOA, the top 20 m temperatures of Icy Strait in northern southeast Alaska during summer were slightly below average (8.8°C) in 2020 relative to the 23 year time series (1997-2019) (Fergusson 2022). A recent study published in the U.S. West Coast suggests that the warming that occurred during 2014-2016 may have been beneficial for rockfish recruitment (Morgan *et al.* 2019).

The primary prey of the adult northern rockfish are euphausiids. Warm conditions tend to be associated with zooplankton communities that are dominated by smaller and less lipid rich species in the GOA (Kimmel *et al.* 2019). There was limited information on zooplankton in 2020. In the inside waters of Icy Strait, northern southeast Alaska, total zooplankton densities were at the 24 year mean and the lipid content of all zooplankton taxa combined examined during 2020 was average for the time series (1997-2020) and similar to 2019 (Fergusson 2022). By taxa, lipid content was above average for the large calanoid copepods, average for hyperiid amphipods, but lower than average for euphausiids, small copepods and gastropods indicating average nutritional quality of the prey field possibly utilized by larval, juvenile, and adult rockfish. In the western GOA, the mean biomass of large calanoids and euphausiids averaged over the top 100m south of Seward Alaska during May were about average in 2020 relative to the time series, 1998-2019 (Fergusson 2022).

Fishery Effects on the Ecosystem

Fishery-specific contribution to bycatch of HAPC biota: In the GOA, bottom trawl fisheries for pollock, deepwater flatfish, and Pacific ocean perch account for most of the observed bycatch of coral, while rockfish fisheries account for little of the bycatch of sea anemones, sea whips, and sea pens. The bottom trawl fisheries for Pacific ocean perch and Pacific cod and the pot fishery for Pacific cod account for most of the observed bycatch of sponges (Table 10-3).

Fishery-specific concentration of target catch in space and time relative to predator needs in space and time (if known) and relative to spawning components: The directed slope rockfish trawl fishery that begins in July is concentrated in known areas of abundance and typically lasts only a few weeks. The annual exploitation rates on rockfish are thought to be quite low. Insemination is likely in the fall or winter, and parturition is likely mostly in the spring. While reproductive activities are probably not directly affected by the commercial fishery, there is evidence of skip spawning often caused by a lack of fertilization (Conrath 2019). If fishing were to reduce the population substantially or cause significant localized depletion it would be possible to increase the amount of observed skip spawning within the stock.

Fishery-specific effects on amount of large size target fish: No evidence for targeting large fish.

Fishery contribution to discards and offal production: Fishery discard rates of northern rockfish during 2009-2022 have been 1.5-9.1%.

Fishery-specific effects on age-at-maturity and fecundity of the target fishery: Unknown.

Fishery-specific effects on EFH living and non-living substrate: Unknown, but the heavy-duty "rockhopper" trawl gear commonly used in the fishery can disturb seafloor habitat. Table 10-3 shows the estimated bycatch of living structure such as benthic urochordates, corals, sponges, sea pens, and sea anemones by the GOA rockfish fisheries. The average bycatch of corals/bryozoans and sponges by rockfish fisheries are a large proportion of the catch of those species taken by all Gulfwide fisheries.

Data Gaps and Research Priorities

Life history and habitat utilization

There is little information on larval, post-larval, or early life history stages of northern rockfish. Habitat requirements for larval, post-larval, and early stages are mostly unknown. Habitat requirements for later stage juvenile and adult fish are anecdotal or conjectural. Research needs to be done on the bottom habitat of the major fishing grounds, on what HAPC biota are found on these grounds, and on what impact bottom trawling may have on these biota. Given the substantial influence of maturity-at-age on management quantities (i.e., ABC) and observations of skip spawning (Conrath 2019) we strongly suggest that continued research be devoted to collecting maturity-at-age data for northern and other GOA rockfish. A first pass at examining the effect of the skip spawning levels reported in (Conrath 2019) shows a decrease in estimated spawning biomass (Figure 10-23). A proposal is currently in the process of being developed that would collect a larger sample size for northern rockfish and compare maturity at age estimates to previous studies. If funded, additional data collected as part of this study would be used to investigate possible time-dependent maturity.

Assessment Data

The highly variable design-based biomass estimates for northern rockfish from bottom trawl survey suggest that the stratified random design of the surveys does a relatively poor job of assessing stock condition of northern rockfish and that a different survey approach may be needed to reduce the variability in biomass estimates. In particular, the last CIE review report recommended that assumptions about extending area-swept estimates of biomass in trawlable versus untrawlable grounds may impact catchability assumptions. The AFSC is currently undertaking a study on habitat classifications so that assumptions about catchability, in particular, time-dependent changes in catchability, can be more rigorously established. To address some of these issues the design-based index has been replaced with a model-based survey biomass index generated by a Vector Autoregressive Spatio-Temporal (VAST) model. The benefits of the VAST model-based approach to survey index standardization are that as a delta-model it partitions the likelihood of trawl survey observations between encounter probability and positive catch rate components, and accounts for spatial and spatio-temporal correlations in survey catch rates. However, this model could benefit from continued examination of appropriate parameterization for northern rockfish which are found in highly "patchy" distributions. Given the high precision of VAST outputs it may prove valuable to the incorporating of an error inflation parameter to increase the variance in VAST models and explore the effect low survey model variance has on resulting assessment outputs.

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Tables

Table 10-1. Commercial catch (t) of dusky rockfish in the Gulf of Alaska, with Gulf-wide values of acceptable biological catch (ABC), total allowable catch (TAC), and percent TAC harvested (% TAC). Values are a combination of foreign observer data, joint venture catch data, and NMFS Regional Office Catch Accounting System data.

Year	Foreign	Joint Venture	Domestic	Total	ABC	TAC	% TAC
1961	800			800			
1962	3,250			3,250			
1963	6,815			6,815			
1964	12,170			12,170			
1965	17,430			17,430			
1966	10,040			10,040			
1967	6,000			6,000			
1968	5,010			5,010			
1969	3,630			3,630			
1970	2,245			2,245			
1971	3,875			3,875			
1972	3,880			3,880			
1973	2,820			2,820			
1974	2,550			2,550			
1975	2,520			2,520			
1976	2,275			2,275			
1977	622			622			
1978	553			554			
1979	666	3		670			
1980	809	1		810			
1981	1,469			1,477			
1982	3,914			3,920			
1983	2,705	911		3,618			
1984	494	497	10	1,002			
1985	1	11	70	185			
1986	1	56	237	248			
1987		1	427	483			
1988[1]			1,107	1,107			
1989			1,527	1,527			
1990			1,697	1,716			
1991[2]			4,528	4,528			
1992			7,770	7,770			
1993[3]			4,820	4,820	5,760	5,760	84
1994			5,966	5,966	5,760	5,760	104
1995			5,635	5,635	5,270	5,270	107
1996			3,340	3,340	5,720	5,270	63
1997			2,935	2,935	5,000	5,000	59
1998			3,055	3,055	5,000	5,000	61
1999			5,409	5,409	4,990	4,990	108
2000			3,333	3,333	5,120	5,120	65
2001			3,133	3,133	4,880	4,880	64
2002			3,339	3,339	4,770	4,770	70
2003			5,256	5,256	5,530	5,530	95
2004			4,811	4,811	4,870	4,870	99

Year	Foreign	Joint Venture	Domestic	Total	ABC	TAC	% TAC
2005			4,522	4,522	5,091	5,091	89
2006			4,958	4,958	5,091	5,091	97
2007[4]			4,187	4,187	4,938	4,938	85
2008			4,052	4,052	4,549	4,549	89
2009			3,952	3,952	4,362	4,362	91
2010			3,902	3,902	5,098	5,098	77
2011			3,443	3,444	4,854	4,854	71
2012			5,077	5,077	5,507	5,507	92
2013			4,879	4,879	5,130	5,130	95
2014			4,277	4,278	5,324	5,324	80
2015			3,944	3,945	4,999	4,999	79
2016			3,437	3,434	4,004	4,004	86
2017			1,836	1,835	3,786	3,786	48
2018			2,440	2,359	3,685	3,685	64
2019			2,748	2,748	4,528	4,528	61
2020			2,375	2,385	4,312	4,312	55
2021			2,376	2,376	5,358	5,358	44
2022[5]			1,876	1,876	5,147	5,147	36

[1]Slope rockfish assemblage management implemented by NPFMC.
[2]Slope rockfish divided into 3 management subgroups: Pacific ocean perch, shortraker/ rougheye, and other slope rockfish.
[3]A fourth management subgroup, northern rockfish, was created.
[4]Central Gulf Rockfish Pilot Project implemented for rockfish fishery.
[5]Catch through 2022-10-28.

Table 10-2. FMP species incidental catch estimates in tons for Gulf of Alaska rockfish targeted fisheries. Blanks = Confidential because of less than three vessels, or not caught. Source: NMFS AKRO Blend/Catch Accounting System via AKFIN 2022-10-28.

Species Group	2018	2019	2020	2021	2022
Arrowtooth Flounder	761	733	890	2,523	2,673
Atka Mackerel	1,140	824	602	674	867
BSAI Skate and GOA Skate, Other	28	26	10	19	13
Flathead Sole	48	40	95	135	74
GOA Deep Water Flatfish	66	39	19	19	34
GOA Demersal Shelf Rockfish	57	56	11	5	5
GOA Dusky Rockfish	2,691	2,151	2,061	2,669	2,458
GOA Rex Sole	136	117	189	99	130
GOA Shallow Water Flatfish	57	34	22	33	26
GOA Skate, Big	6	5	6	4	4
GOA Skate, Longnose	46	28	24	31	28
GOA Thornyhead Rockfish	362	177	138	113	215
Halibut		0	2	0	
Northern Rockfish	2,152	2,313	2,317	2,303	1,794
Octopus	3	9	1	1	0
Other Rockfish	992	669	522	975	900
Pacific Cod	401	322	170	660	626
Pacific Ocean Perch	22,172	22,258	22,881	27,399	24,916
Pollock	917	686	647	1,559	1,779
Rougheye Rockfish	317	320	89	162	219
Sablefish	708	801	647	893	912
Sculpin	65	53	30		
Shark	48	62	33	32	12
Shortraker Rockfish	269	269	225	240	179
Squid	29				

Table 10-3. Non-FMP species bycatch estimates in tons for Gulf of Alaska rockfish targeted fisheries. Conf. = Confidential because of less than three vessels. Source: NMFS AKRO Blend/Catch Accounting System via AKFIN 2022-10-28.

Species Group	2018	2019	2020	2021	2022
Benthic urochordata	0.07	0.4	0.12	0.01	3.69
Birds - Northern Fulmar	Conf	Conf	-	Conf	-
Bivalves	Conf	Conf	0	0.04	Conf
Brittle star unidentified	0.01	0.02	0.01	0.05	0.02
Corals Bryozoans - Corals Bryozoans Unidentified	1.36	0.88	0.17	1.73	0.32
Eelpouts	0.22	0	Conf	Conf	Conf
Eulachon	0.13	0.27	0.1	-	-
Giant Grenadier	1690.57	753.99	302.08	252.11	196.28
Greenlings	4.51	9.57	3.5	3.43	3.62
Grenadier - Rattail Grenadier Unidentified	5.33	4.01	1.73	0.19	2.79
Hermit crab unidentified	0.01	Conf	0	0.01	0.01
Invertebrate unidentified	0.11	0.07	Conf	0.06	0.01
Lanternfishes (myctophidae)	Conf	0.06	0.02	0.05	-
Misc crabs	0.45	0.33	0.1	0.1	0.09
Misc crustaceans	0.13	0.2	0.07	0.06	0.05
Misc fish	137.36	358.89	87.16	164.01	77.54
Pacific Hake	0.07	Conf	0.03	-	-
Pandalid shrimp	0.07	0.11	0.17	0.29	0.09
Scypho jellies	0.92	8.43	3.52	3.19	0.93
Sea anemone unidentified	0.46	1.52	1.24	1.78	0.93
Sea pens whips	0	0.03	0	Conf	0.02
Sea star	4.33	1.36	1.14	1.5	1.29
Snails	5.67	1.79	0.08	1.18	0.11
Sponge unidentified	13.66	5.88	0.52	1.22	5.97
State-managed Rockfish	52.88	46.43	53.11	12.35	33.26
Stichaeidae	0.51	-	Conf	-	Conf
urchins dollars cucumbers	0.31	0.21	0.91	0.23	0.22
Birds - Shearwaters	-	Conf	-	-	-
Capelin	-	Conf	Conf	-	-
Misc deep fish	-	Conf	-	-	Conf
Other osmerids	-	Conf	0.98	0.08	0.08
Polychaete unidentified	-	Conf	-	-	Conf
Squid	-	10.87	31.8	27.77	43.12
Bristlemouths	-	-	Conf	-	-
Misc inverts (worms etc)	-	-	0	0	Conf
Gunnels	-	-	-	Conf	-
Pacific Sand lance	-	-	-	Conf	-
Sculpin	-	-	-	23.52	39.3
Smelt (Family Osmeridae)	-	-	-	0.23	0.26

Table 10-4. Prohibited Species Catch (PSC) estimates reported in tons for halibut and herring, and thousands of animals for crab and salmon, by year, for the GOA rockfish fishery 2014-2018. Source: NMFS AKRO Blend/Catch Accounting System PSCNQ via AKFIN 2022-10-28.

Species Group	2018	2019	2020	2021	2022
Bairdi Tanner Crab	321	64	1,146	2,279	180
Blue King Crab	0	0	0	0	0
Chinook Salmon	336	410	655	1,042	1,116
Golden (Brown) King Crab	324	223	60	114	136
Halibut	100	115	111	179	128
Herring	0	2	0	0	1
Non-Chinook Salmon	325	380	723	1,628	4,002
Opilio Tanner (Snow) Crab	0	0	0	0	0
Red King Crab	0	0	0	0	0

Table 10-5. Gulf of Alaska discard rates (percent of the total catch discarded within management categories) of northern rockfish.

Year	% discard	Year	% discard	Year	% discard
1993	26.5	2004	7.8	2015	4.6
1994	17.7	2005	4.2	2016	5.5
1995	12.7	2006	9.1	2017	7.9
1996	16.6	2007	2.6	2018	3.6
1997	28.0	2008	4.9	2019	5.6
1998	18.4	2009	3.1	2020	1.4
1999	11.3	2010	1.5	2021	1.6
2000	10.0	2011	3.9	2022	1.5
2001	17.7	2012	2.5		
2002	10.0	2013	4.1		
2003	9.4	2014	3.8		

Table 10-6. Summary of key management measures and the time series of catch, ABC, and TAC for northern rockfish in the Gulf of Alaska. Catch through 2022-10-28.

Year	Catch	ABC	TAC	% TAC	Management measure
1961	800				
1962	3,250				
1963	6,815				
1964	12,170				
1965	17,430				
1966	10,040				
1967	6,000				
1968	5,010				
1969	3,630				
1970	2,245				
1971	3,875				
1972	3,880				
1973	2,820				
1974	2,550				
1975	2,520				
1976	2,275				
1977	622				
1978	554				
1979	670				
1980	810				
1981	1,477				
1982	3,920				
1983	3,618				
1984	1,002				
1985	185				
1986	248				
1987	483				
1988	1,107				The slope rockfish assemblage, including northern rockfish, was one of three management groups for Sebastes implemented by the North Pacific Management Council. Previously, Sebastes in Alaska were managed as "Pacific ocean perch complex" or "other rockfish"
1989	1,527				
1990	1,716				
1991	4,528				Slope assemblage split into three management subgroups with separate ABCs and TACs: POP, shortraker/rougheye rockfish, other slope species
1992	7,770				
1993	4,820	5,760	5,760	84	Designated as a subgroup of slope rockfish with separate ABC and TAC
1994	5,966	5,760	5,760	104	
1995	5,635	5,270	5,270	107	
1996	3,340	5,720	5,270	63	
1997	2,935	5,000	5,000	59	
1998	3,055	5,000	5,000	61	

Year	Catch	ABC	TAC	% TAC	Management measure
1999	5,409	4,990	4,990	108	Eastern GOA divided into West Yakutat and East Yakutat/Southeast Outside due to trawl closure in Eastern GOA. The ABC and TAC for northern rockfish in Eastern GOA allocated to West Yakutat ABC as part of "other slope rockfish".
2000	3,333	5,120	5,120	65	Amendment 41 prohibited trawling in the Eastern Gulf (40 degrees W). Preliminary age-structured model results presented to PT
2001	3,133	4,880	4,880	64	Assessed with an age structured model using AD Model Builder software.
2002	3,339	4,770	4,770	70	
2003	5,256	5,530	5,530	95	
2004	4,811	4,870	4,870	99	
2005	4,522	5,091	5,091	89	
2006	4,958	5,091	5,091	97	
2007	4,187	4,938	4,938	85	Amendment 68 created the Central Gulf Rockfish Pilot Project
2008	4,052	4,549	4,549	89	
2009	3,952	4,362	4,362	91	
2010	3,902	5,098	5,098	77	
2011	3,444	4,854	4,854	71	
2012	5,077	5,507	5,507	92	NPFMCs Central GOA Rockfish Program implemented
2013	4,879	5,130	5,130	95	
2014	4,278	5,324	5,324	80	
2015	3,945	4,999	4,999	79	
2016	3,434	4,004	4,004	86	
2017	1,835	3,786	3,786	48	
2018	2,359	3,685	3,685	64	
2019	2,748	4,528	4,528	61	
2020	2,385	4,312	4,312	55	
2021	2,376	5,358	5,358	44	
2022	1,876	5,147	5,147	36	

Table 10-7. Fishery length compositions for northern rockfish in the Gulf of Alaska. Lengths below 22 are pooled and lengths greater than 47 are pooled. Survey size compositions are not used in model.

Length (cm)	1991	1992	1993	1994	1995	1996	1997	2003	2007	2009	2011	2013	2015	2017	2019	2021
15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
16	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
17	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
18	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
19	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
21	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
22	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
23	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0000
24	0.001	0.000	0.000	0.000	0.002	0.000	0.002	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.0002
25	0.002	0.000	0.000	0.000	0.004	0.000	0.006	0.001	0.000	0.000	0.000	0.001	0.001	0.000	0.002	0.0002
26	0.003	0.000	0.001	0.000	0.007	0.000	0.014	0.001	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.0018
27	0.004	0.000	0.001	0.001	0.009	0.001	0.020	0.002	0.001	0.001	0.000	0.001	0.001	0.001	0.002	0.0020
28	0.007	0.001	0.002	0.002	0.008	0.002	0.021	0.002	0.002	0.001	0.000	0.002	0.002	0.002	0.002	0.0011
29	0.010	0.003	0.005	0.004	0.010	0.003	0.021	0.007	0.002	0.001	0.001	0.003	0.004	0.010	0.001	0.0040
30	0.023	0.006	0.010	0.007	0.013	0.007	0.019	0.012	0.007	0.004	0.001	0.003	0.005	0.006	0.003	0.0046
31	0.041	0.015	0.024	0.017	0.015	0.006	0.014	0.030	0.009	0.009	0.002	0.006	0.009	0.010	0.006	0.0068
32	0.072	0.032	0.046	0.030	0.021	0.013	0.015	0.045	0.023	0.010	0.005	0.004	0.010	0.014	0.005	0.0099
33	0.123	0.053	0.079	0.070	0.043	0.028	0.029	0.070	0.038	0.020	0.011	0.009	0.011	0.020	0.014	0.0136
34	0.180	0.094	0.109	0.116	0.081	0.058	0.054	0.075	0.060	0.038	0.023	0.019	0.018	0.030	0.021	0.0257
35	0.196	0.139	0.156	0.175	0.127	0.122	0.115	0.084	0.085	0.077	0.051	0.035	0.033	0.030	0.035	0.0286
36	0.145	0.157	0.166	0.199	0.156	0.177	0.159	0.075	0.105	0.098	0.076	0.066	0.054	0.043	0.055	0.0453
37	0.091	0.154	0.127	0.171	0.164	0.189	0.173	0.083	0.124	0.110	0.103	0.099	0.110	0.067	0.075	0.0598
38	0.047	0.131	0.100	0.100	0.135	0.150	0.150	0.102	0.138	0.110	0.106	0.120	0.140	0.118	0.095	0.0871
39	0.023	0.095	0.068	0.053	0.086	0.103	0.091	0.110	0.127	0.116	0.120	0.137	0.153	0.162	0.139	0.1416
40	0.012	0.061	0.048	0.025	0.040	0.066	0.052	0.095	0.109	0.121	0.128	0.122	0.142	0.170	0.153	0.1583
41	0.007	0.033	0.034	0.012	0.020	0.037	0.024	0.078	0.081	0.104	0.124	0.124	0.115	0.134	0.141	0.1500
42	0.003	0.013	0.018	0.007	0.015	0.018	0.012	0.057	0.045	0.073	0.103	0.100	0.090	0.087	0.101	0.1166
43	0.003	0.004	0.005	0.005	0.011	0.008	0.005	0.039	0.023	0.043	0.073	0.070	0.048	0.046	0.069	0.0680
44	0.002	0.004	0.001	0.003	0.008	0.004	0.002	0.016	0.011	0.028	0.038	0.041	0.028	0.025	0.039	0.0413
45+	0.006	0.004	0.000	0.005	0.020	0.009	0.001	0.012	0.009	0.035	0.033	0.038	0.023	0.022	0.042	0.0334
n_s	15,321	15,207	10,732	8,138	11,537	7,942	5,261	6,025	7,101	6,045	5,121	6,418	7,176	3,529	5,385	4,547
n_h	147	125	94	90	121	108	73	374	489	456	403	500	554	378	439	364

Table 10-8. Fishery age compositions for northern rockfish in the Gulf of Alaska.

Length (cm)	1998	1999	2000	2001	2002	2004	2005	2006	2008	2010	2012	2014	2016	2018	2020
2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0015	0.0000
5	0.0000	0.0065	0.0017	0.0000	0.0000	0.0013	0.0000	0.000	0.0000	0.0000	0.0017	0.0013	0.0000	0.0000	0.0000
6	0.0040	0.0032	0.0239	0.0111	0.0000	0.0147	0.0000	0.006	0.0000	0.0000	0.0000	0.0025	0.0000	0.0015	0.0043
7	0.0060	0.0065	0.0051	0.0554	0.0325	0.0080	0.0213	0.002	0.0060	0.0000	0.0069	0.0101	0.0016	0.0046	0.0130
8	0.0341	0.0000	0.0154	0.0244	0.1510	0.0362	0.0450	0.046	0.0201	0.0119	0.0000	0.0025	0.0344	0.0215	0.0130
9	0.0221	0.0422	0.0188	0.0310	0.0698	0.1113	0.0664	0.064	0.0262	0.0239	0.0034	0.0101	0.0213	0.0154	0.0173
10	0.0321	0.0130	0.0427	0.0377	0.0552	0.1756	0.1469	0.070	0.0785	0.0318	0.0223	0.0089	0.0180	0.0338	0.0281
11	0.0582	0.0292	0.0308	0.0488	0.0422	0.0496	0.1635	0.132	0.0684	0.0596	0.0412	0.0114	0.0197	0.0446	0.0540
12	0.0703	0.0390	0.0581	0.0421	0.0438	0.0349	0.0521	0.070	0.0483	0.1153	0.0274	0.0406	0.0098	0.0400	0.0281
13	0.0944	0.0487	0.0530	0.0532	0.0471	0.0362	0.0166	0.048	0.0926	0.0716	0.0943	0.0659	0.0115	0.0308	0.0216
14	0.0944	0.0617	0.0479	0.0510	0.0325	0.0282	0.0308	0.034	0.0765	0.0517	0.1046	0.0494	0.0279	0.0231	0.0194
15	0.0683	0.1266	0.0735	0.0399	0.0308	0.0268	0.0379	0.034	0.0302	0.0676	0.0772	0.0773	0.0623	0.0323	0.0216
16	0.0783	0.0649	0.0940	0.0532	0.0471	0.0322	0.0261	0.020	0.0221	0.0517	0.0566	0.0900	0.0508	0.0385	0.0130
17	0.0341	0.0584	0.0667	0.0843	0.0682	0.0147	0.0190	0.016	0.0121	0.0278	0.0892	0.0608	0.0754	0.0354	0.0216
18	0.0341	0.0422	0.0598	0.0599	0.0666	0.0255	0.0308	0.038	0.0060	0.0179	0.0480	0.0710	0.0869	0.0631	0.0302
19	0.0221	0.0195	0.0239	0.0443	0.0325	0.0456	0.0261	0.028	0.0121	0.0159	0.0223	0.0659	0.0590	0.0615	0.0324
20	0.0261	0.0227	0.0222	0.0266	0.0260	0.0576	0.0332	0.020	0.0221	0.0239	0.0257	0.0608	0.0672	0.0569	0.0562
21	0.0442	0.0325	0.0103	0.0355	0.0227	0.0349	0.0450	0.040	0.0201	0.0219	0.0120	0.0253	0.0967	0.0415	0.0605
22	0.0502	0.0292	0.0427	0.0177	0.0211	0.0295	0.0237	0.050	0.0161	0.0318	0.0103	0.0215	0.0705	0.0615	0.0497
23	0.0361	0.0747	0.0342	0.0333	0.0130	0.0228	0.0261	0.036	0.0382	0.0139	0.0086	0.0152	0.0279	0.0446	0.0497
24	0.0301	0.0422	0.0462	0.0333	0.0292	0.0107	0.0095	0.024	0.0503	0.0139	0.0240	0.0279	0.0213	0.0323	0.0259
25	0.0221	0.0097	0.0222	0.0443	0.0438	0.0121	0.0095	0.010	0.0282	0.0338	0.0206	0.0114	0.0295	0.0215	0.0454
26	0.0241	0.0260	0.0291	0.0421	0.0276	0.0214	0.0047	0.012	0.0302	0.0298	0.0240	0.0266	0.0131	0.0215	0.0324
27	0.0120	0.0162	0.0137	0.0133	0.0114	0.0389	0.0261	0.018	0.0221	0.0159	0.0326	0.0266	0.0164	0.0262	0.0173
28	0.0100	0.0422	0.0205	0.0200	0.0081	0.0295	0.0308	0.018	0.0060	0.0199	0.0377	0.0215	0.0066	0.0154	0.0346
29	0.0261	0.0357	0.0239	0.0089	0.0097	0.0121	0.0237	0.034	0.0141	0.0139	0.0103	0.0101	0.0082	0.0200	0.0194
30	0.0201	0.0227	0.0410	0.0177	0.0114	0.0174	0.0284	0.032	0.0262	0.0239	0.0240	0.0317	0.0164	0.0354	0.0238
31	0.0060	0.0292	0.0188	0.0200	0.0114	0.0107	0.0071	0.022	0.0282	0.0139	0.0120	0.0177	0.0148	0.0262	0.0108
32	0.0100	0.0130	0.0137	0.0133	0.0114	0.0080	0.0024	0.006	0.0342	0.0239	0.0103	0.0127	0.0213	0.0200	0.0194
33	0.0120	0.0032	0.0103	0.0089	0.0097	0.0094	0.0071	0.006	0.0322	0.0278	0.0154	0.0177	0.0148	0.0246	0.0324
34	0.0000	0.0065	0.0017	0.0044	0.0049	0.0067	0.0166	0.012	0.0181	0.0378	0.0154	0.0076	0.0082	0.0185	0.0302
35	0.0020	0.0065	0.0034	0.0022	0.0000	0.0094	0.0047	0.012	0.0181	0.0199	0.0189	0.0114	0.0098	0.0123	0.0108
36	0.0000	0.0000	0.0034	0.0022	0.0032	0.0094	0.0047	0.020	0.0060	0.0040	0.0223	0.0139	0.0033	0.0108	0.0130
37	0.0020	0.0065	0.0017	0.0111	0.0049	0.0027	0.0024	0.008	0.0181	0.0080	0.0137	0.0127	0.0049	0.0108	0.0130
38	0.0060	0.0032	0.0017	0.0067	0.0000	0.0027	0.0024	0.000	0.0181	0.0099	0.0137	0.0101	0.0082	0.0077	0.0216
39	0.0020	0.0032	0.0051	0.0000	0.0016	0.0013	0.0047	0.002	0.0121	0.0119	0.0103	0.0089	0.0082	0.0062	0.0216
40	0.0040	0.0032	0.0068	0.0022	0.0049	0.0013	0.0000	0.002	0.0060	0.0139	0.0120	0.0114	0.0082	0.0046	0.0173
41	0.0000	0.0000	0.0034	0.0000	0.0000	0.0000	0.0000	0.000	0.0020	0.0099	0.0051	0.0025	0.0115	0.0031	0.0086
42	0.0000	0.0065	0.0017	0.0000	0.0000	0.0040	0.0024	0.002	0.0080	0.0040	0.0017	0.0051	0.0033	0.0062	0.0173
43	0.0020	0.0032	0.0034	0.0000	0.0000	0.0027	0.0024	0.002	0.0040	0.0020	0.0034	0.0025	0.0082	0.0077	0.0086
44	0.0000	0.0000	0.0000	0.0000	0.0016	0.0000	0.0000	0.004	0.0000	0.0099	0.0017	0.0038	0.0049	0.0015	0.0151
45+	0.0000	0.0000	0.0034	0.0000	0.0032	0.0040	0.0000	0.000	0.0221	0.0139	0.0189	0.0152	0.0180	0.0154	0.0281
n_s	498	308	585	451	616	746	422	500	497	503	583	789	610	650	463
n_h	51	160	187	156	187	270	211	206	311	311	420	406	394	351	273

Table 10-9. GOA northern rockfish biomass estimates, standard errors, and confidence intervals, based on results of NMFS bottom trawl surveys using VAST with lognormal error that is used in model 22.1.

Year	Biomass (t)	SE	Lower CI	Upper CI
1990	106,646	17,868	71,625	141,666
1993	108,278	16,265	76,398	140,157
1996	181,895	36,959	109,456	254,335
1999	173,850	51,359	73,186	274,513
2001	253,261	36,072	182,559	323,963
2003	107,229	17,205	73,507	140,951
2005	236,085	30,274	176,748	295,422
2007	206,102	30,783	145,768	266,437
2009	89,847	13,779	62,840	116,854
2011	155,676	29,431	97,991	213,360
2013	369,021	78,320	215,514	522,528
2015	115,822	29,105	58,777	172,868
2017	179,318	28,563	123,335	235,300
2019	110,105	17,522	75,763	144,448
2021	74,074	11,429	51,672	96,475

Table 10-10. GOA northern rockfish biomass estimates, standard errors, and confidence intervals, based on results of NMFS bottom trawl surveys using a design-based estimator.

Year	Biomass (t)	SE	Lower CI	Upper CI
1984	39,334	11,307	17,171	61,496
1987	136,417	39,148	59,686	213,147
1990	107,076	45,482	17,931	196,222
1993	104,992	36,853	32,760	177,224
1996	98,965	26,596	46,838	151,093
1999	242,187	147,109	0	530,521
2001	343,614	205,475	0	746,344
2003	66,310	31,955	3,677	128,943
2005	358,999	132,432	99,432	618,565
2007	221,226	84,579	55,451	387,002
2009	89,896	28,888	33,276	146,515
2011	173,642	67,117	42,092	305,192
2013	370,454	220,613	0	802,855
2015	48,933	16,689	16,223	81,644
2017	150,326	67,890	17,261	283,391
2019	86,725	30,706	26,542	146,908
2021	90,670	31,688	28,562	152,779

Table 10-11. NMFS trawl survey age compositions for northern rockfish in the Gulf of Alaska.

Length (cm)	1990	1993	1996	1999	2001	2003	2005	2007	2009	2011	2013	2015	2017	2019	2021
2	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.001	0.003	0.002	0.000	0.005	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.002	0.003	0.001	0.002	0.002	0.002	0.001	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
5	0.029	0.009	0.002	0.011	0.005	0.035	0.001	0.001	0.003	0.000	0.000	0.000	0.001	0.003	0.001
6	0.054	0.011	0.011	0.003	0.013	0.021	0.014	0.007	0.000	0.000	0.001	0.001	0.002	0.002	0.000
7	0.026	0.011	0.006	0.009	0.040	0.014	0.037	0.004	0.007	0.000	0.004	0.006	0.002	0.004	0.007
8	0.041	0.064	0.021	0.009	0.016	0.096	0.052	0.029	0.015	0.002	0.004	0.006	0.009	0.010	0.004
9	0.054	0.120	0.041	0.042	0.038	0.126	0.047	0.091	0.022	0.003	0.002	0.006	0.007	0.020	0.026
10	0.045	0.066	0.053	0.028	0.072	0.056	0.061	0.058	0.051	0.015	0.006	0.023	0.003	0.038	0.014
11	0.058	0.103	0.085	0.079	0.060	0.036	0.047	0.074	0.071	0.019	0.023	0.011	0.015	0.014	0.024
12	0.035	0.044	0.076	0.069	0.040	0.029	0.033	0.063	0.053	0.023	0.028	0.007	0.015	0.023	0.028
13	0.054	0.049	0.077	0.054	0.063	0.021	0.011	0.083	0.060	0.040	0.032	0.012	0.011	0.025	0.024
14	0.082	0.040	0.040	0.056	0.049	0.051	0.021	0.031	0.062	0.039	0.038	0.020	0.011	0.009	0.007
15	0.097	0.024	0.033	0.078	0.050	0.033	0.012	0.018	0.038	0.021	0.052	0.050	0.014	0.013	0.013
16	0.051	0.052	0.039	0.092	0.054	0.043	0.020	0.026	0.034	0.029	0.070	0.055	0.030	0.025	0.024
17	0.051	0.031	0.016	0.016	0.044	0.000	0.032	0.020	0.021	0.059	0.044	0.073	0.043	0.032	0.022
18	0.007	0.040	0.034	0.072	0.058	0.018	0.031	0.010	0.034	0.017	0.070	0.055	0.038	0.043	0.025
19	0.011	0.028	0.054	0.019	0.029	0.030	0.008	0.020	0.032	0.016	0.031	0.030	0.037	0.046	0.052
20	0.066	0.004	0.088	0.013	0.022	0.061	0.039	0.028	0.027	0.024	0.037	0.045	0.040	0.039	0.046
21	0.066	0.023	0.028	0.030	0.016	0.012	0.046	0.033	0.016	0.022	0.013	0.066	0.056	0.079	0.032
22	0.046	0.034	0.031	0.022	0.012	0.020	0.019	0.038	0.010	0.029	0.023	0.022	0.040	0.032	0.048
23	0.019	0.044	0.030	0.025	0.027	0.011	0.013	0.049	0.027	0.021	0.029	0.027	0.044	0.046	0.047
24	0.009	0.044	0.033	0.030	0.045	0.007	0.012	0.011	0.041	0.039	0.033	0.014	0.014	0.050	0.031
25	0.010	0.046	0.027	0.020	0.029	0.014	0.021	0.012	0.046	0.031	0.030	0.025	0.022	0.038	0.048
26	0.034	0.007	0.052	0.015	0.042	0.025	0.025	0.014	0.026	0.015	0.011	0.020	0.014	0.024	0.020
27	0.006	0.017	0.014	0.034	0.012	0.030	0.022	0.027	0.017	0.047	0.033	0.023	0.027	0.012	0.016
28	0.012	0.022	0.015	0.025	0.009	0.054	0.037	0.028	0.014	0.034	0.032	0.024	0.026	0.015	0.014
29	0.002	0.006	0.028	0.024	0.024	0.034	0.036	0.030	0.030	0.018	0.035	0.017	0.026	0.016	0.012
30	0.010	0.000	0.006	0.016	0.021	0.016	0.038	0.033	0.014	0.027	0.015	0.027	0.013	0.005	0.040
31	0.010	0.002	0.007	0.024	0.014	0.000	0.023	0.024	0.012	0.023	0.038	0.021	0.014	0.015	0.022
32	0.009	0.010	0.004	0.045	0.019	0.000	0.040	0.016	0.025	0.022	0.002	0.029	0.046	0.026	0.007
33	0.005	0.005	0.015	0.010	0.011	0.042	0.018	0.010	0.022	0.025	0.014	0.025	0.034	0.027	0.025
34	0.000	0.006	0.007	0.008	0.008	0.010	0.046	0.020	0.011	0.030	0.024	0.014	0.020	0.018	0.044
35	0.000	0.006	0.005	0.000	0.017	0.012	0.027	0.014	0.012	0.052	0.009	0.020	0.041	0.028	0.037
36	0.000	0.009	0.000	0.003	0.004	0.007	0.024	0.023	0.021	0.036	0.031	0.018	0.035	0.007	0.022
37	0.000	0.001	0.007	0.000	0.000	0.019	0.011	0.009	0.019	0.035	0.036	0.035	0.026	0.010	0.018
38	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.014	0.028	0.039	0.017	0.010	0.025	0.030	0.024
39	0.000	0.014	0.002	0.012	0.002	0.003	0.011	0.005	0.013	0.017	0.020	0.020	0.030	0.012	0.015
40	0.000	0.002	0.000	0.002	0.011	0.011	0.011	0.010	0.010	0.019	0.012	0.035	0.030	0.024	0.018
41	0.000	0.000	0.000	0.003	0.009	0.000	0.004	0.004	0.008	0.030	0.018	0.018	0.017	0.021	0.011
42	0.000	0.000	0.003	0.000	0.000	0.000	0.000	0.001	0.006	0.028	0.023	0.012	0.011	0.011	0.015
43	0.000	0.000	0.004	0.000	0.000	0.000	0.004	0.002	0.005	0.014	0.007	0.009	0.013	0.016	0.019
44	0.000	0.000	0.000	0.000	0.000	0.000	0.013	0.003	0.007	0.008	0.003	0.016	0.030	0.022	0.014
45+	0.000	0.000	0.000	0.000	0.007	0.000	0.026	0.010	0.029	0.029	0.052	0.052	0.068	0.072	0.084
n_s	331	242	462	278	466	216	417	605	651	430	495	465	462	368	512
n_h	12	17	19	27	85	22	72	82	69	74	68	56	80	64	68

Table 10-12. NMFS trawl survey length compositions for northern rockfish in the Gulf of Alaska. Lengths below 22 are pooled and lengths greater than 47 are pooled. Survey size compositions are not used in model.

Length (cm)	1990	1993	1996	1999	2001	2003	2005	2007	2009	2011	2013	2015	2017	2019	2021
15	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
17	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
18	0.000	0.001	0.001	0.000	0.003	0.000	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.000
19	0.001	0.001	0.000	0.001	0.002	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.001
20	0.001	0.000	0.001	0.001	0.002	0.001	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
21	0.001	0.001	0.001	0.001	0.002	0.001	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
22	0.003	0.002	0.002	0.002	0.002	0.002	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.001
23	0.005	0.003	0.002	0.003	0.001	0.004	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000
24	0.012	0.003	0.002	0.002	0.002	0.006	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002
25	0.011	0.007	0.003	0.002	0.002	0.007	0.000	0.002	0.001	0.000	0.001	0.002	0.001	0.001	0.002
26	0.030	0.005	0.007	0.006	0.004	0.018	0.001	0.002	0.002	0.000	0.001	0.001	0.000	0.002	0.002
27	0.024	0.007	0.008	0.002	0.005	0.011	0.001	0.006	0.003	0.000	0.001	0.001	0.002	0.001	0.004
28	0.017	0.008	0.005	0.006	0.008	0.007	0.001	0.002	0.002	0.000	0.001	0.004	0.001	0.004	0.003
29	0.017	0.007	0.008	0.002	0.005	0.010	0.064	0.006	0.002	0.000	0.001	0.002	0.001	0.002	0.003
30	0.013	0.012	0.009	0.003	0.010	0.015	0.034	0.003	0.008	0.000	0.004	0.002	0.004	0.004	0.007
31	0.022	0.015	0.016	0.002	0.011	0.021	0.012	0.007	0.006	0.001	0.002	0.006	0.004	0.005	0.007
32	0.038	0.041	0.020	0.027	0.023	0.040	0.013	0.018	0.013	0.002	0.004	0.007	0.008	0.009	0.011
33	0.090	0.055	0.027	0.031	0.017	0.064	0.021	0.038	0.012	0.004	0.005	0.009	0.007	0.019	0.006
34	0.126	0.091	0.034	0.035	0.053	0.077	0.025	0.062	0.032	0.015	0.012	0.013	0.008	0.018	0.018
35	0.139	0.147	0.060	0.054	0.051	0.063	0.032	0.070	0.040	0.012	0.013	0.007	0.014	0.023	0.024
36	0.118	0.161	0.121	0.078	0.121	0.078	0.052	0.084	0.056	0.018	0.034	0.025	0.016	0.040	0.037
37	0.102	0.123	0.118	0.128	0.127	0.071	0.055	0.093	0.082	0.044	0.040	0.053	0.032	0.059	0.041
38	0.075	0.105	0.135	0.184	0.167	0.099	0.089	0.090	0.094	0.061	0.116	0.098	0.046	0.081	0.061
39	0.062	0.065	0.119	0.127	0.106	0.095	0.107	0.123	0.135	0.103	0.160	0.120	0.115	0.149	0.091
40	0.029	0.053	0.095	0.110	0.116	0.082	0.117	0.131	0.126	0.139	0.153	0.166	0.135	0.198	0.137
41	0.027	0.038	0.093	0.094	0.056	0.070	0.108	0.113	0.137	0.190	0.189	0.180	0.170	0.172	0.161
42	0.017	0.023	0.052	0.047	0.062	0.049	0.081	0.080	0.102	0.144	0.136	0.123	0.150	0.106	0.154
43	0.007	0.012	0.032	0.038	0.018	0.048	0.077	0.036	0.067	0.127	0.080	0.091	0.135	0.066	0.128
44	0.006	0.008	0.018	0.011	0.009	0.014	0.077	0.021	0.039	0.063	0.029	0.043	0.080	0.025	0.066
45+	0.006	0.006	0.009	0.003	0.016	0.046	0.030	0.011	0.034	0.073	0.018	0.046	0.068	0.013	0.035
n_s	3,091	4,384	4,239	3,471	3,810	2,941	4,556	4,723	2,849	2,460	3,138	2,325	2,570	2,237	2,088
n_h	48	106	131	124	106	126	147	139	132	89	86	95	92	74	70

Table 10-13. Likelihood values and estimates of key parameters for a select few models for GOA northern rockfish.

Likelihoods	base	m18.2b	m22	m22.1	m22.1a	m22.1b
Catch	0.126	0.098	0.083	0.091	0.173	0.246
Survey biomass	11.504	11.041	6.148	6.022	6.023	22.268
Fishery ages	37.429	40.917	41.078	40.177	100.979	99.894
Survey ages	68.741	67.118	66.057	69.160	119.246	119.669
Fishery lengths	46.267	49.996	50.704	67.907	131.253	131.536
Maturity	23.501	23.501	23.501	23.501	23.501	23.501
Data	164.067	169.171	164.070	183.356	357.674	373.612
Penalties/Priors						
Recruitment devs	8.931	8.780	8.757	8.640	9.847	10.024
F regularity	5.601	5.499	5.471	5.457	5.942	6.074
M prior	0.067	0.062	0.020	0.014	0.012	0.048
q prior	0.374	0.255	0.099	0.052	0.015	0.096
Objective function	249.270	253.990	248.650	267.750	443.720	460.080
Parameter estimates						
# parameters	181	185	185	185	185	185
M	0.059	0.059	0.059	0.059	0.060	0.059
q	0.678	0.725	0.819	0.865	0.926	0.821
rec	3.487	3.515	3.530	3.504	3.409	3.465
F40	0.061	0.061	0.061	0.061	0.061	0.061
Projected total biomass	102,661	101,479	99,365	95,559	86,908	108,108
Projected spawning biomass	42,774	42,135	41,102	39,463	36,402	45,876
B100	84,832	85,282	83,815	82,350	78,318	89,078
B40	33,933	34,113	33,526	32,940	31,327	35,631
ABC	5,357	5,251	5,147	4,972	4,573	5,726

Table 10-14. Estimated numbers (thousands), fishery selectivity, and survey selectivity of northern rockfish in the Gulf of Alaska based on the preferred model. Also shown are schedules of age-specific weight and female maturity.

		Percent		Selectivity	
Age	Abundance	Mature	Weight	Fishery	Survey
2	10,793	0	29.7	0.00	0.01
3	9,581	1	74.4	0.00	0.02
4	8,381	1	136.0	0.00	0.03
5	6,915	3	209.2	0.01	0.06
6	5,905	5	288.5	0.03	0.11
7	4,257	9	369.4	0.13	0.19
8	4,664	16	448.5	0.41	0.32
9	3,247	26	523.6	0.76	0.48
10	3,411	40	593.2	0.94	0.65
11	2,105	56	656.6	0.99	0.79
12	2,665	71	713.6	1.00	0.88
13	3,046	83	764.2	1.00	0.93
14	2,786	90	808.7	1.00	0.97
15	2,279	95	847.7	1.00	0.98
16	1,729	97	881.5	1.00	0.99
17	1,859	98	910.8	1.00	1.00
18	1,045	99	936.0	1.00	1.00
19	962	100	957.7	1.00	1.00
20	1,937	100	976.2	1.00	1.00
21	3,455	100	992.1	1.00	1.00
22	2,535	100	1,005.6	1.00	1.00
23	3,180	100	1,017.1	1.00	1.00
24	7,098	100	1,026.9	1.00	1.00
25	3,780	100	1,035.2	1.00	1.00
26	3,119	100	1,042.2	1.00	1.00
27	4,660	100	1,048.2	1.00	1.00
28	6,442	100	1,053.3	1.00	1.00
29	1,113	100	1,057.6	1.00	1.00
30	1,422	100	1,061.2	1.00	1.00
31	1,429	100	1,064.3	1.00	1.00
32	1,868	100	1,066.9	1.00	1.00
33	808	100	1,069.1	1.00	1.00
34	1,812	100	1,070.9	1.00	1.00
35	1,476	100	1,072.5	1.00	1.00
36	987	100	1,073.8	1.00	1.00
37	1,767	100	1,074.9	1.00	1.00
38	3,436	100	1,075.9	1.00	1.00
39	895	100	1,076.7	1.00	1.00
40	1,822	100	1,077.4	1.00	1.00
41	1,375	100	1,077.9	1.00	1.00
42	917	100	1,078.4	1.00	1.00
43	728	100	1,078.8	1.00	1.00
44	755	100	1,079.2	1.00	1.00
45+	8,200	100	1,079.5	1.00	1.00

Table 10-15. Comparison of 2022 estimated time series of female spawning biomass, 6+ biomass (age 6 and greater), catch/(6+ biomass), and the number of age-2+ recruits for northern rockfish in the Gulf of Alaska compared with 2020 estimates.

	Spawning biomass		6+ biomass		Catch/6+ biomass		Age-2+ recruits	
Year	Previous	Current	Previous	Current	Previous	Current	Previous	Current
1977	19,509	19,280	73,537	71,058	0.008	0.009	33.7	21.6
1978	21,720	21,387	79,199	77,896	0.007	0.007	57.1	61.5
1979	24,584	24,115	86,756	85,139	0.008	0.008	45.7	42.4
1980	27,962	27,377	91,891	91,524	0.009	0.009	20.3	22.3
1981	31,621	30,988	101,063	98,146	0.015	0.015	15.2	20.1
1982	35,071	34,471	115,480	112,949	0.034	0.035	26.1	23.8
1983	37,429	36,896	126,165	122,570	0.029	0.030	30.1	33.2
1984	39,922	39,407	131,820	128,407	0.008	0.008	45.8	40.8
1985	43,788	43,218	138,123	135,814	0.001	0.001	19.0	18.4
1986	48,456	47,775	146,750	144,118	0.002	0.002	62.9	64.5
1987	53,438	52,651	155,767	153,924	0.003	0.003	31.7	30.2
1988	58,283	57,460	167,987	165,107	0.007	0.007	14.6	15.4
1989	62,494	61,723	173,746	170,772	0.009	0.009	20.2	21.0
1990	66,113	65,441	188,477	185,546	0.009	0.009	23.3	23.7
1991	69,455	68,867	196,957	193,647	0.023	0.023	9.8	9.7
1992	71,620	71,045	198,077	194,990	0.039	0.040	20.5	20.8
1993	72,490	71,854	195,942	193,140	0.025	0.025	13.8	14.6
1994	74,558	73,870	196,690	194,146	0.030	0.031	13.1	13.4
1995	75,846	75,129	192,575	190,306	0.029	0.030	9.5	9.7
1996	76,658	75,964	190,258	188,267	0.018	0.018	52.5	51.4
1997	77,723	77,104	188,347	186,807	0.016	0.016	34.8	34.1
1998	78,249	77,740	186,092	184,914	0.016	0.017	20.8	20.9
1999	78,136	77,752	182,384	181,552	0.030	0.030	23.5	23.2
2000	76,539	76,279	185,927	184,793	0.018	0.018	40.3	39.9
2001	75,697	75,549	189,146	187,771	0.017	0.017	15.7	16.4
2002	74,996	74,932	189,890	188,492	0.018	0.018	11.7	12.0
2003	74,530	74,504	190,836	189,339	0.028	0.028	14.1	15.0
2004	73,765	73,719	193,743	191,973	0.025	0.025	6.6	7.7
2005	73,724	73,627	192,063	190,430	0.024	0.024	3.2	3.5
2006	74,099	73,941	189,129	187,668	0.026	0.026	3.2	3.5
2007	74,288	74,079	185,627	184,488	0.023	0.023	5.2	5.7
2008	74,569	74,344	180,656	180,004	0.022	0.023	5.0	4.8
2009	74,457	74,260	174,274	174,022	0.023	0.023	6.7	5.8
2010	73,759	73,639	167,284	167,406	0.023	0.023	6.9	6.5
2011	72,362	72,361	160,281	160,779	0.021	0.021	5.3	6.5
2012	70,476	70,623	153,404	154,122	0.033	0.033	5.4	5.3
2013	67,227	67,525	145,185	145,864	0.034	0.033	4.4	3.8
2014	63,650	64,082	137,300	137,968	0.031	0.031	5.4	5.7
2015	60,139	60,669	129,825	130,807	0.030	0.030	6.4	5.0
2016	56,731	57,319	122,833	123,859	0.028	0.028	8.4	6.7
2017	53,622	54,230	116,286	117,228	0.016	0.016	7.9	5.7
2018	51,370	51,975	111,687	112,686	0.021	0.021	9.4	7.5
2019	48,961	49,547	106,963	107,621	0.026	0.026	9.7	8.3
2020	46,462	47,015	102,570	102,714	0.026	0.023	10.6	9.4
2021		44,738		98,216		0.024		10.2
2022		42,555		94,330		0.020		10.8

Table 10-16. Estimated time series of number at age-4 recruits (thousands), total biomass, and female spawning biomass with 95% confidence bounds for northern rockfish in the Gulf of Alaska, from this year's model MCMC results.

	Age 2+ recruits			Total biomass			Spawning biomass		
Year	Mean	2.5%	97.5%	Mean	2.5%	97.5%	Mean	2.5%	97.5%
1977	21,632	28	4,224	78,863	51,080	113,676	19,280	10,938	30,630
1978	61,483	141	6,399	87,174	57,328	124,024	21,387	12,584	33,007
1979	42,418	49	5,717	96,564	63,960	135,731	24,115	14,682	36,162
1980	22,282	25	3,753	106,369	71,108	148,982	27,377	17,017	40,250
1981	20,150	34	3,232	116,187	77,982	161,696	30,988	19,544	44,900
1982	23,763	22	3,321	125,181	84,204	173,587	34,471	21,801	49,318
1983	33,196	77	4,742	131,554	87,563	183,354	36,896	23,255	53,045
1984	40,816	25	4,186	138,341	91,782	193,530	39,407	24,777	56,708
1985	18,434	28	4,246	147,389	98,446	205,102	43,218	27,500	61,705
1986	64,457	183	5,830	158,062	106,749	219,208	47,775	30,860	67,800
1987	30,158	57	3,849	168,707	114,595	232,880	52,651	34,371	74,225
1988	15,354	29	2,256	178,686	121,616	245,214	57,460	37,904	80,243
1989	21,000	46	2,292	187,393	128,293	256,618	61,723	40,885	85,370
1990	23,688	239	2,470	194,853	133,580	266,484	65,441	43,536	90,399
1991	9,740	25	1,412	200,820	137,707	273,547	68,868	46,029	94,920
1992	20,769	161	2,035	202,824	138,067	277,274	71,045	47,259	98,140
1993	14,619	44	1,765	200,351	134,010	276,160	71,854	47,182	100,246
1994	13,387	58	1,525	199,780	132,808	276,335	73,870	48,203	103,297
1995	9,654	23	1,262	196,931	129,845	274,725	75,129	48,500	105,794
1996	51,424	1,366	4,135	194,645	127,393	273,536	75,964	48,500	107,178
1997	34,118	497	3,141	194,933	127,078	274,690	77,104	49,154	108,853
1998	20,909	72	2,309	195,825	127,251	276,588	77,740	49,431	110,011
1999	23,201	108	2,298	196,825	127,796	278,835	77,752	49,313	110,161
2000	39,905	895	3,589	196,100	126,196	279,883	76,279	47,826	108,925
2001	16,400	32	1,726	197,516	126,399	282,852	75,549	47,070	107,929
2002	12,007	52	1,509	198,877	127,098	285,168	74,932	46,492	107,252
2003	15,038	109	1,591	199,591	126,880	287,118	74,504	46,043	106,970
2004	7,747	31	889	197,577	123,845	285,640	73,718	45,143	106,808
2005	3,531	13	517	194,994	121,079	283,541	73,626	44,550	107,899
2006	3,504	14	497	191,586	118,009	280,361	73,941	44,327	108,918
2007	5,680	33	648	186,684	113,471	275,091	74,079	44,024	109,796
2008	4,816	24	645	181,586	108,984	268,839	74,344	43,562	111,245
2009	5,793	22	752	175,830	104,146	261,874	74,260	43,206	111,158
2010	6,484	32	818	169,580	99,215	254,115	73,639	42,427	110,691
2011	6,520	27	849	162,969	94,116	246,928	72,361	41,128	109,705
2012	5,253	19	715	156,532	89,288	238,459	70,623	39,638	107,687
2013	3,815	14	568	148,267	82,681	228,274	67,525	37,143	103,977
2014	5,687	20	784	140,180	76,182	218,036	64,082	34,490	99,646
2015	5,000	14	825	132,734	70,486	209,261	60,669	31,855	95,316
2016	6,695	17	1,095	125,763	64,996	200,590	57,319	29,306	91,007
2017	5,738	13	1,237	119,466	60,198	191,877	54,230	27,109	87,037
2018	7,494	14	1,836	114,994	57,191	184,963	51,975	25,579	84,114
2019	8,266	14	1,944	110,257	53,916	178,030	49,547	23,949	80,749
2020	9,440	16	2,989	105,483	50,331	171,112	47,015	22,114	77,206
2021	10,168	17	3,267	101,489	47,223	165,565	44,738	20,576	73,891
2022	10,793	17	5,793	97,950	43,839	161,538	42,555	18,985	70,925
2023	17,580	486	88,112	95,559			39,463	17,219	66,192
2024	17,580	467	97,234	92,840			37,360	16,344	61,687

Table 10-17. Estimates of key parameters with Hessian estimates of standard deviation σ, MCMC standard deviations σ_MCMC, and 95% Bayesian credible intervals (BCI) derived from MCMC.

Parameter	μ	μ MCMC	Median MCMC	σ	σ MCMC	BCI Lower	BCI Upper
q	0.865	1.079	0.987	0.193	0.414	0.588	2.300
M	0.059	0.060	0.060	0.003	0.003	0.055	0.066
F_{40}	0.061	0.071	0.068	0.016	0.021	0.040	0.125
Spawning biomass projected	39,463	36,146	34,439	12,249	12,303	17,219	66,192
ABC	4,972	5,130	4,804	2,001	2,416	1,465	10,888

Table 10-18. Set of projections of spawning biomass (SB) and yield for northern rockfish in the Gulf of Alaska. Six harvest scenarios designed to satisfy the requirements of Amendment 56, NEPA, and MSFCMA. For a description of scenarios see section *Harvest Recommendations*.

Year	Maximum permissible F	Author's F (Estimated catches)	Half max.1	5-year average F	No Fishing	Overfished	Approaching overfished
			Spawning biomass (mt)				
2022	41,399	41,399	41,399	41,399	41,399	41,399	41,399
2023	39,069	39,445	39,467	39,544	39,869	38,910	39,069
2024	36,059	37,470	37,539	37,833	39,082	35,481	36,059
2025	33,425	35,398	35,838	36,328	38,435	32,512	33,290
2026	31,201	32,966	34,380	35,051	37,956	30,056	30,723
2027	29,448	30,960	33,181	34,024	37,674	28,161	28,723
2028	28,145	29,440	32,262	33,273	37,621	26,763	27,236
2029	27,266	28,374	31,658	32,824	37,834	25,820	26,219
2030	26,796	27,740	31,356	32,705	38,350	25,302	25,638
2031	26,707	27,508	31,375	32,930	39,198	25,175	25,455
2032	26,944	27,620	31,690	33,482	40,376	25,375	25,607
2033	27,416	27,983	32,239	34,298	41,833	25,803	25,995
2034	28,019	28,491	33,004	35,286	43,479	26,354	26,510
2035	28,665	29,057	33,891	36,360	45,226	26,940	27,067
			Fishing mortality				
2022	0.023	0.023	0.023	0.023	0.023	0.023	0.023
2023	0.061	0.032	0.031	0.025		0.074	0.074
2024	0.061	0.031	0.031	0.025		0.074	0.074
2025	0.061	0.061	0.031	0.025		0.073	0.073
2026	0.058	0.061	0.031	0.025		0.067	0.067
2027	0.054	0.057	0.031	0.025		0.062	0.062
2028	0.052	0.054	0.030	0.025		0.059	0.059
2029	0.050	0.052	0.029	0.025		0.057	0.057
2030	0.049	0.051	0.029	0.025		0.056	0.056
2031	0.049	0.051	0.029	0.025		0.055	0.055
2032	0.049	0.051	0.029	0.025		0.056	0.056
2033	0.050	0.051	0.030	0.025		0.057	0.057
2034	0.051	0.052	0.030	0.025		0.058	0.058
2035	0.052	0.053	0.031	0.025		0.059	0.059
			Yield (mt)				
2022	2,003	2,003	2,003	2,003	2,003	2,003	2,003
2023	4,965	4,965	2,519	2,039		5,927	4,965
2024	4,611	4,742	2,410	1,961		5,440	4,611
2025	4,313	4,560	2,319	1,898		4,964	5,149
2026	3,849	4,292	2,248	1,849		4,281	4,472
2027	3,467	3,827	2,189	1,814		3,801	3,953
2028	3,210	3,505	2,101	1,796		3,483	3,604
2029	3,075	3,321	2,066	1,803		3,313	3,412
2030	3,058	3,265	2,089	1,838		3,281	3,364
2031	3,125	3,300	2,150	1,889		3,347	3,417
2032	3,244	3,392	2,229	1,947		3,474	3,532
2033	3,385	3,509	2,311	2,005		3,629	3,677
2034	3,533	3,635	2,390	2,062		3,791	3,830
2035	3,679	3,762	2,467	2,119		3,953	3,984

Figures

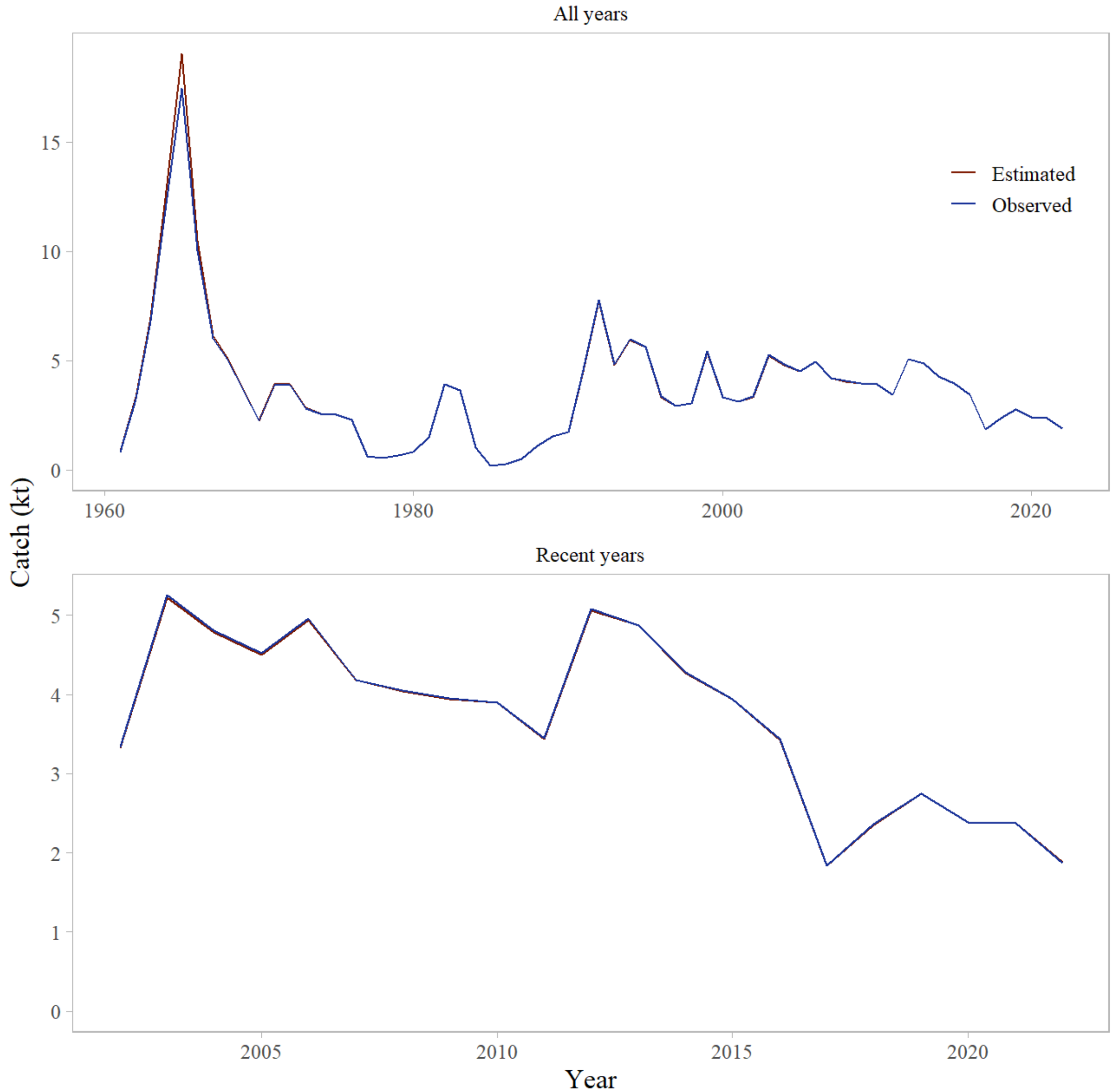

Figure 10-1. Estimated and observed long-term and recent commercial catch of GOA northern rockfish in the Gulf of Alaska.

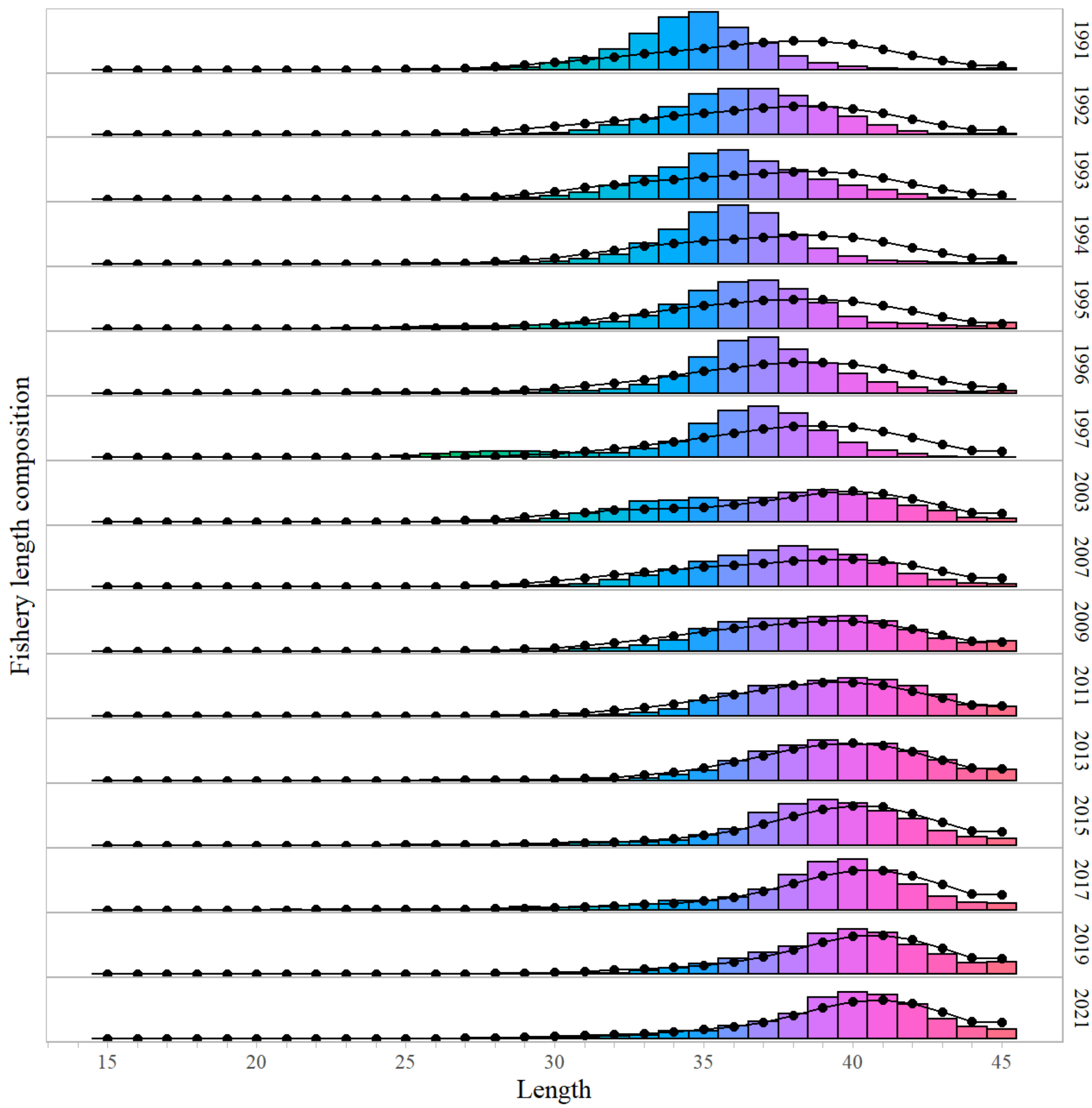

Figure 10-2. Fishery length compositions for GOA northern rockfish. Observed values are bars, lines are the predicted lengths from author's recommended model.

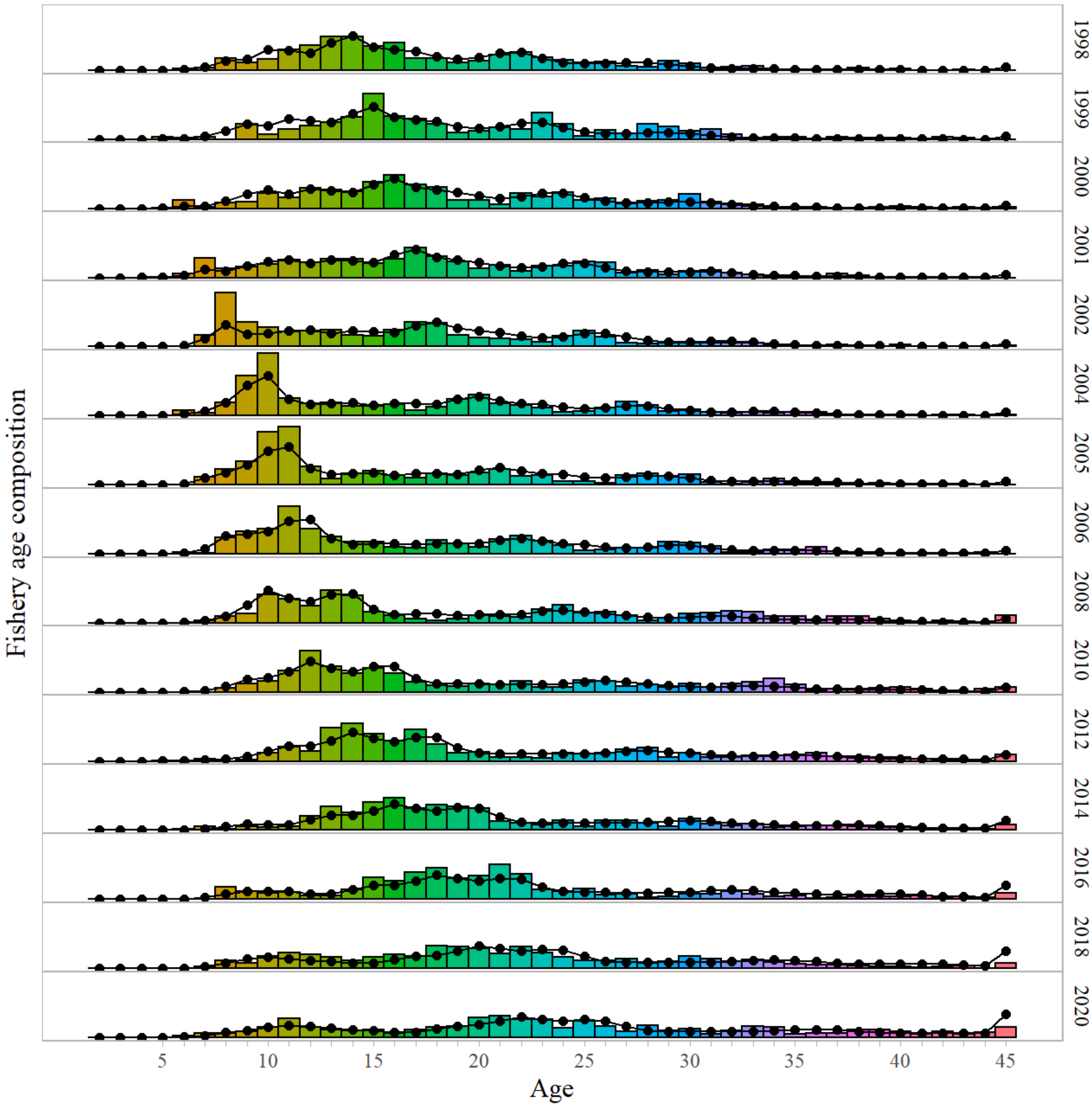

Figure 10-3. Fishery age compositions for GOA northern rockfish. Observed values are bars, lines are the predicted lengths from author's recommended model.

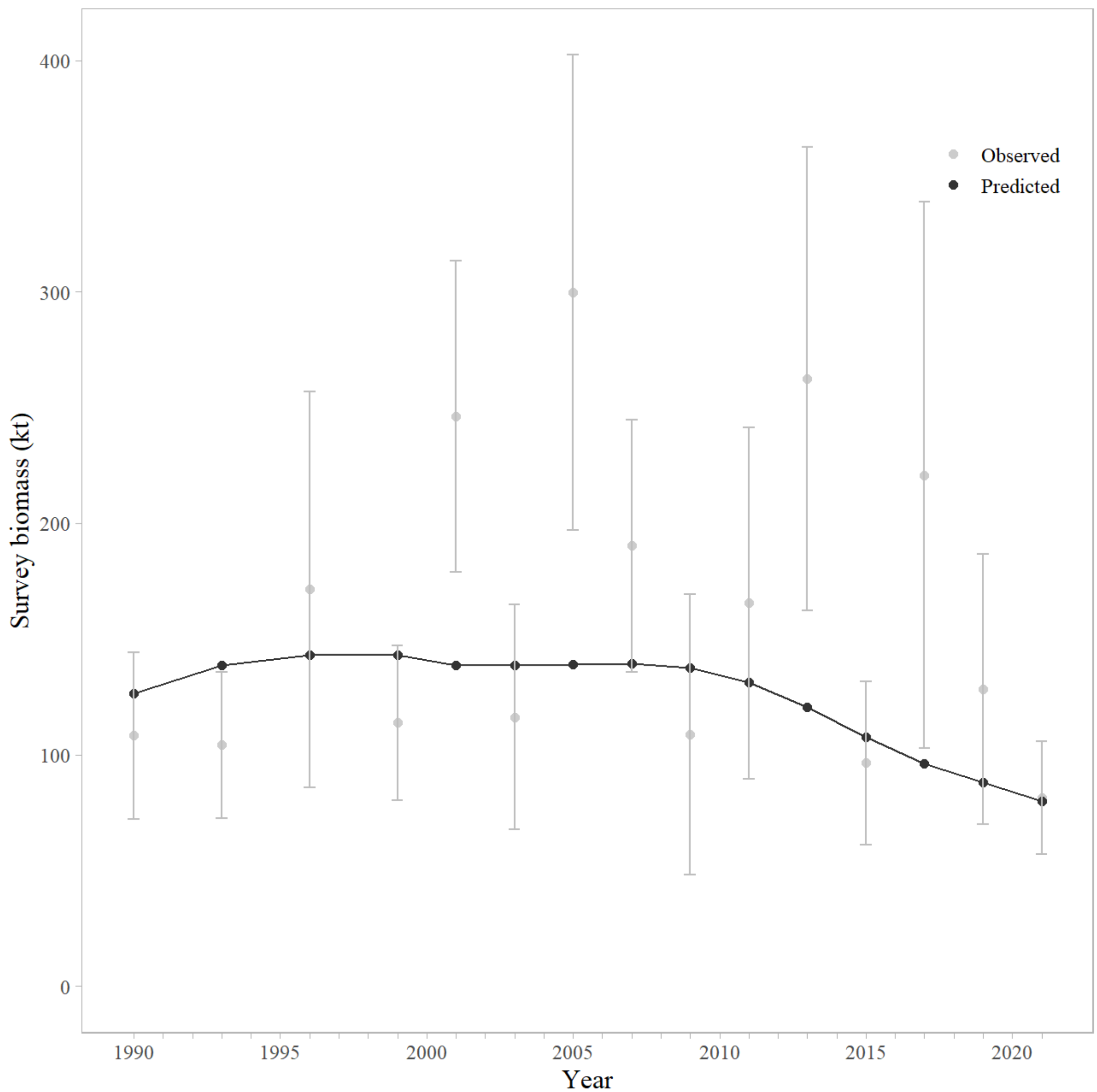

Figure 10-4. Observed (geostatistical model-based estimates) and predicted GOA northern rockfish trawl survey biomass based on the 2022 recommended model. Error bars are approximate asymptotic 95% confidence intervals of model error.

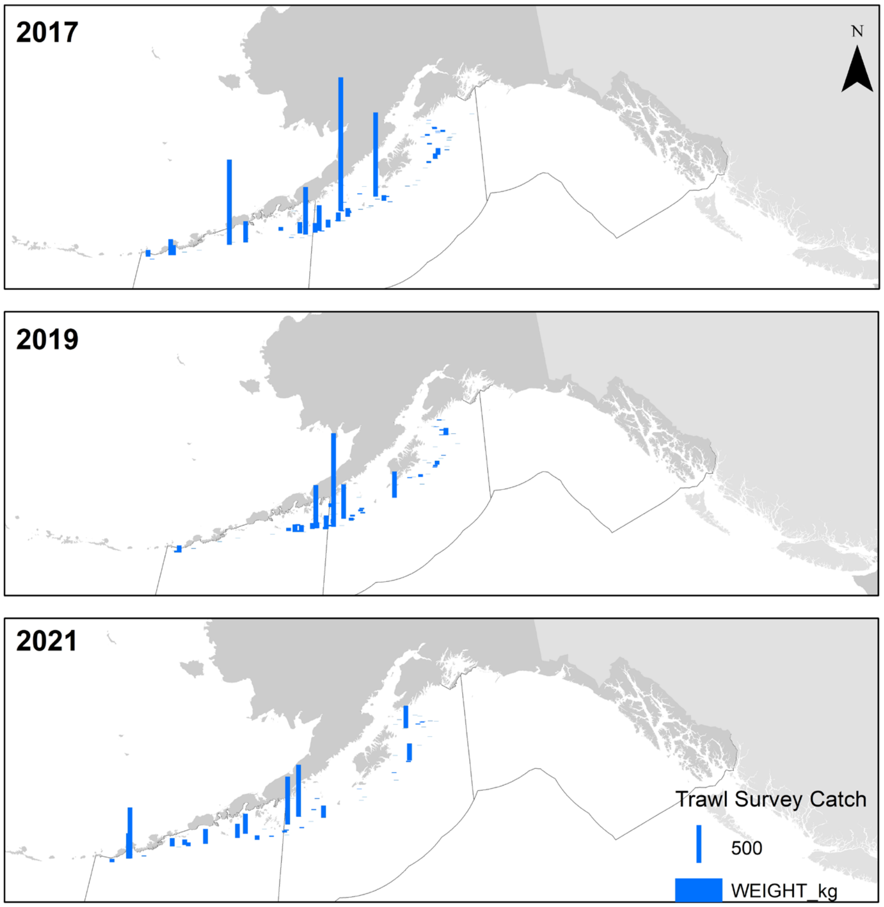

Figure 10-5. Spatial distribution of northern rockfish in the Gulf of Alaska during the 2017, 2019, and 2021 NMFS trawl surveys.

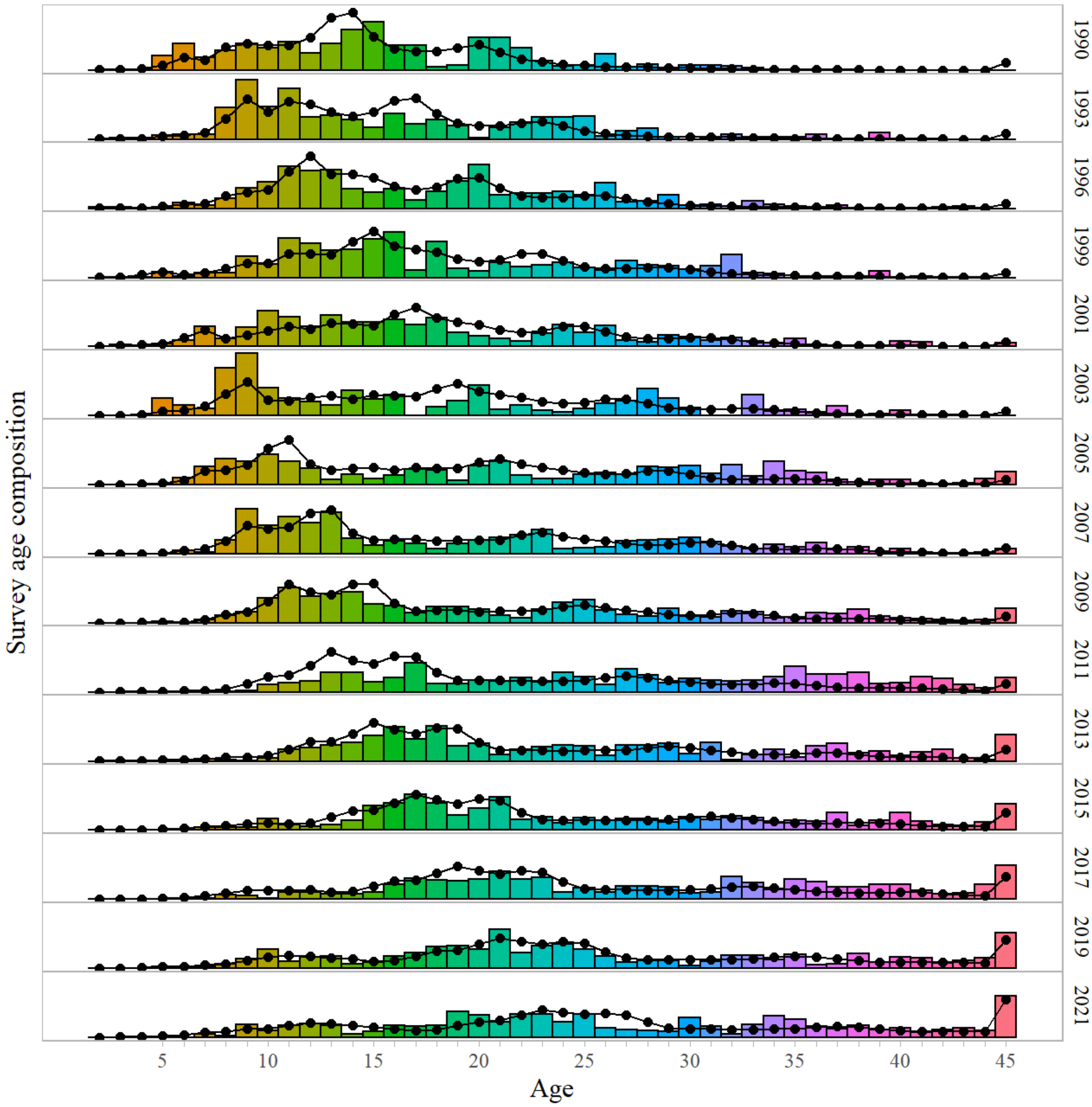

Figure 10-6. Survey age compositions for GOA northern rockfish. Observed values are bars, lines are the predicted lengths from author's recommended model.

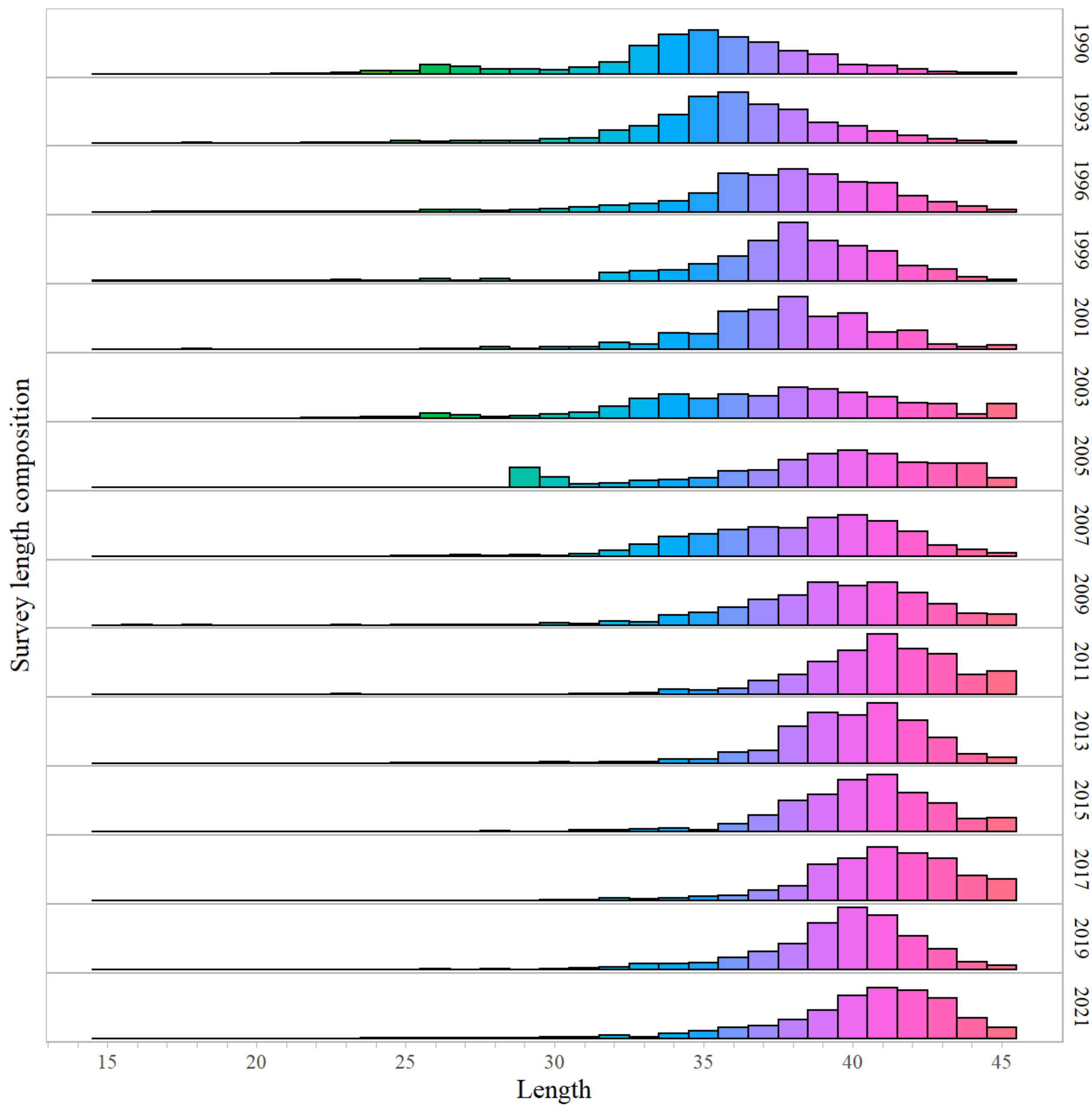

Figure 10-7. Survey length compositions (not used in model) for GOA northern rockfish.

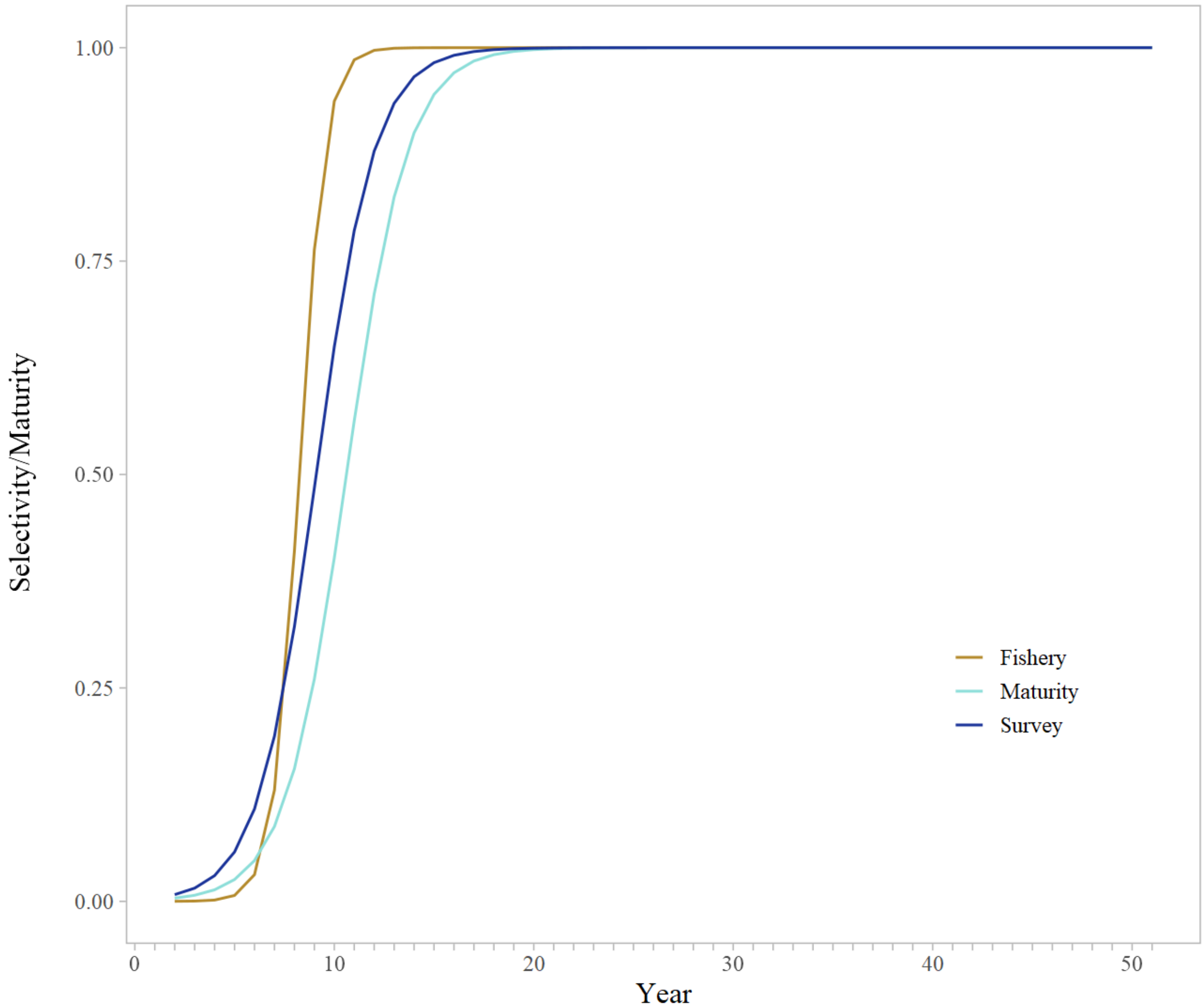

Figure 10-8. Estimated maturity, fishery and survey selectivities for GOA northern rockfish from the 2022 model.

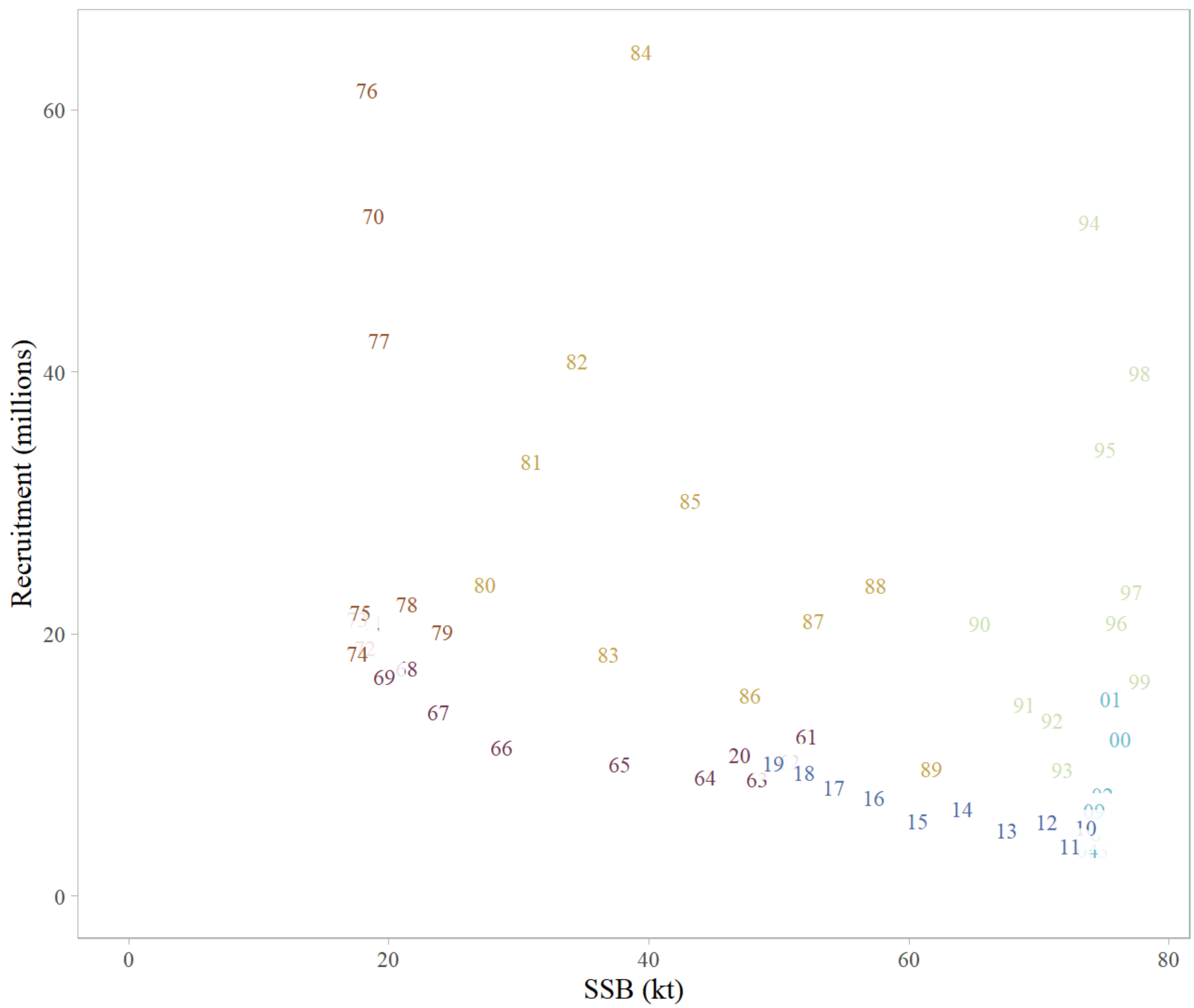

Figure 10-9. Scatterplot of spawner-recruit estimates for the GOA northern rockfish author's recommended model.

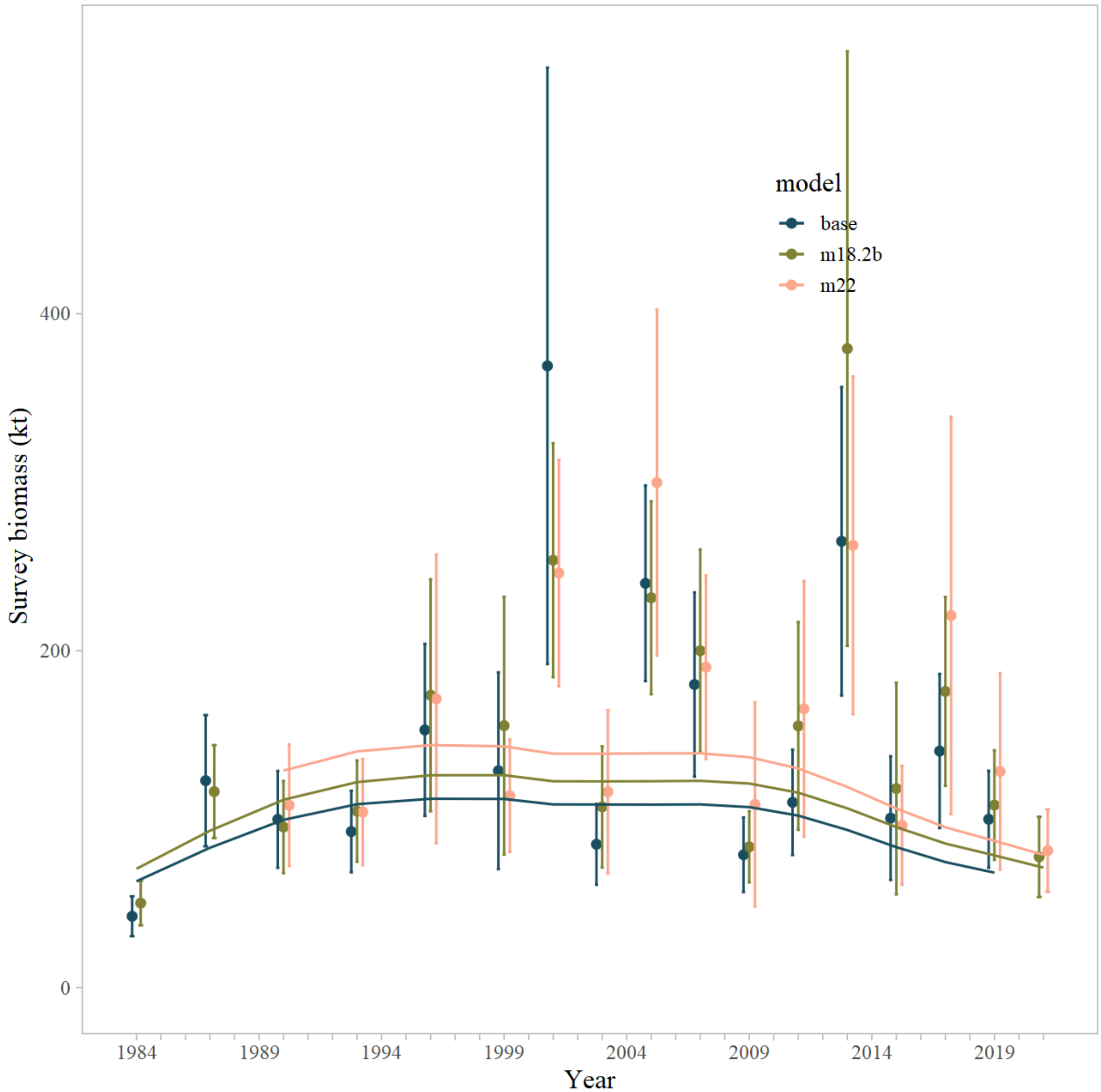

Figure 10-10. Comparisons of observed and predicted GOA northern rockfish trawl survey biomass for different base model variants. Error bars are approximate asymptotic 95% confidence intervals of model error. for different model variants.

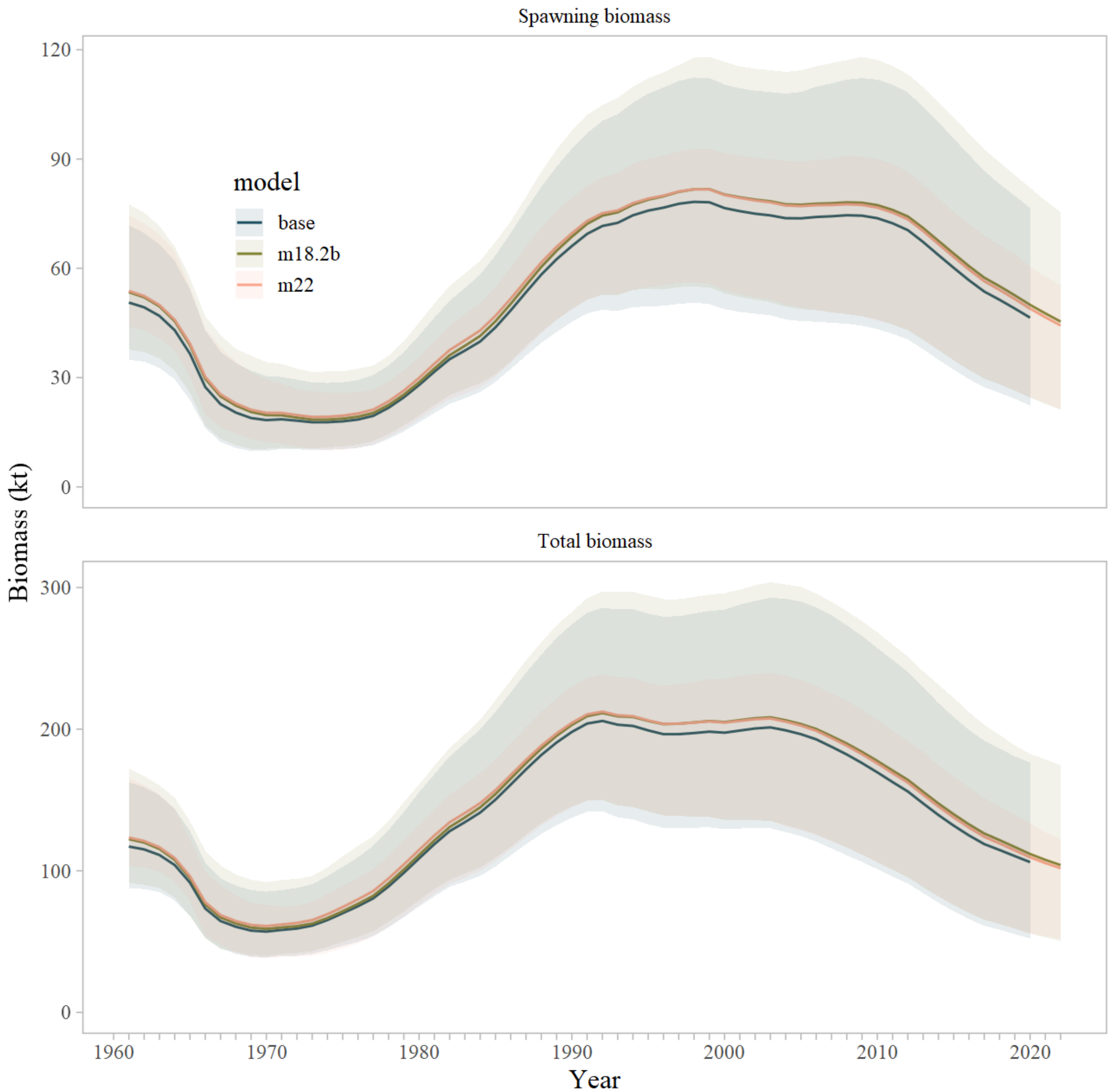

Figure 10-11. Comparisons of spawning and total biomass for different base model variants.

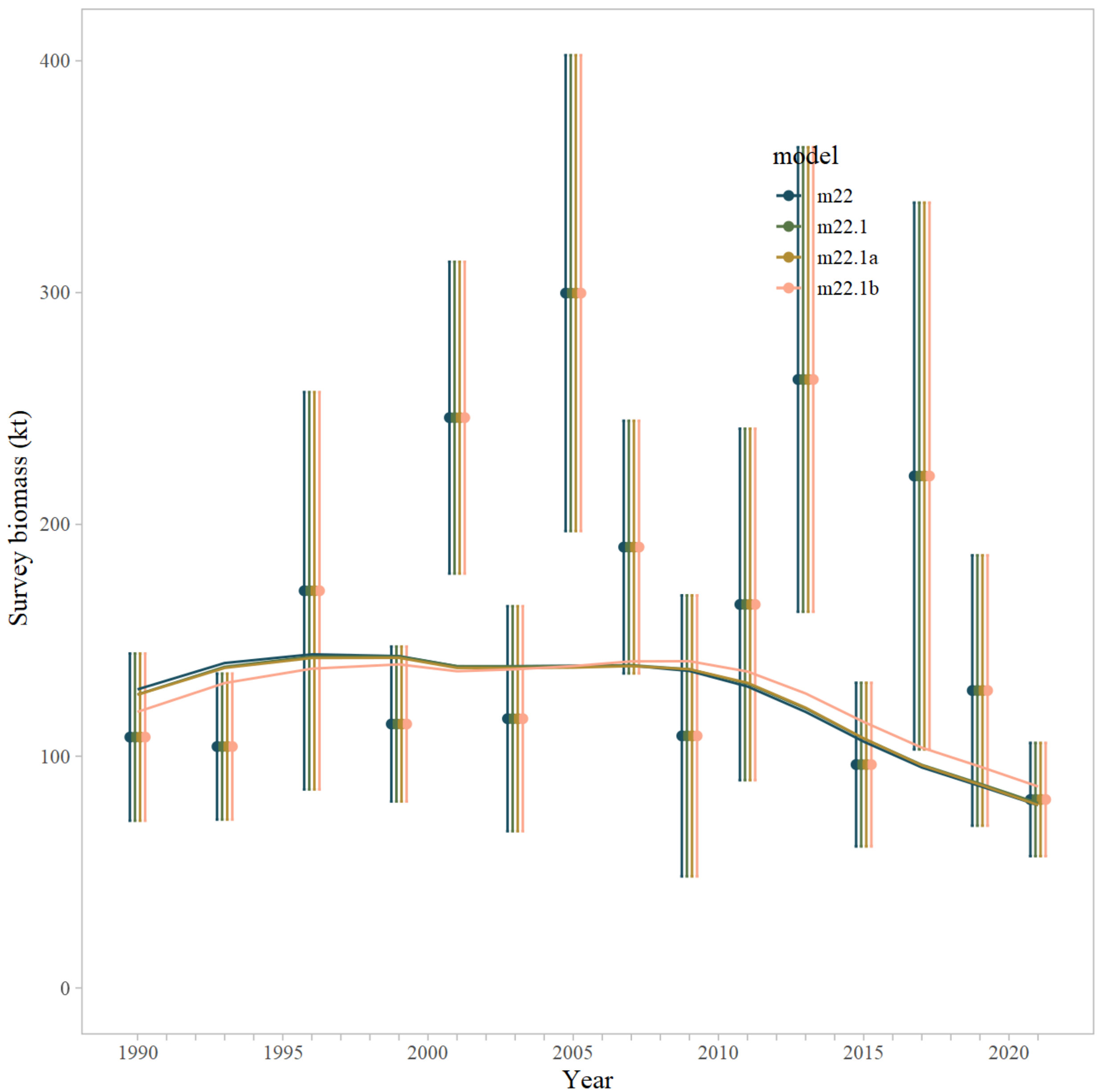

Figure 10-12. Comparisons of observed and predicted GOA northern rockfish trawl survey biomass for model 22 (m22) variants. Error bars are approximate asymptotic 95% confidence intervals of model error. for different model variants.

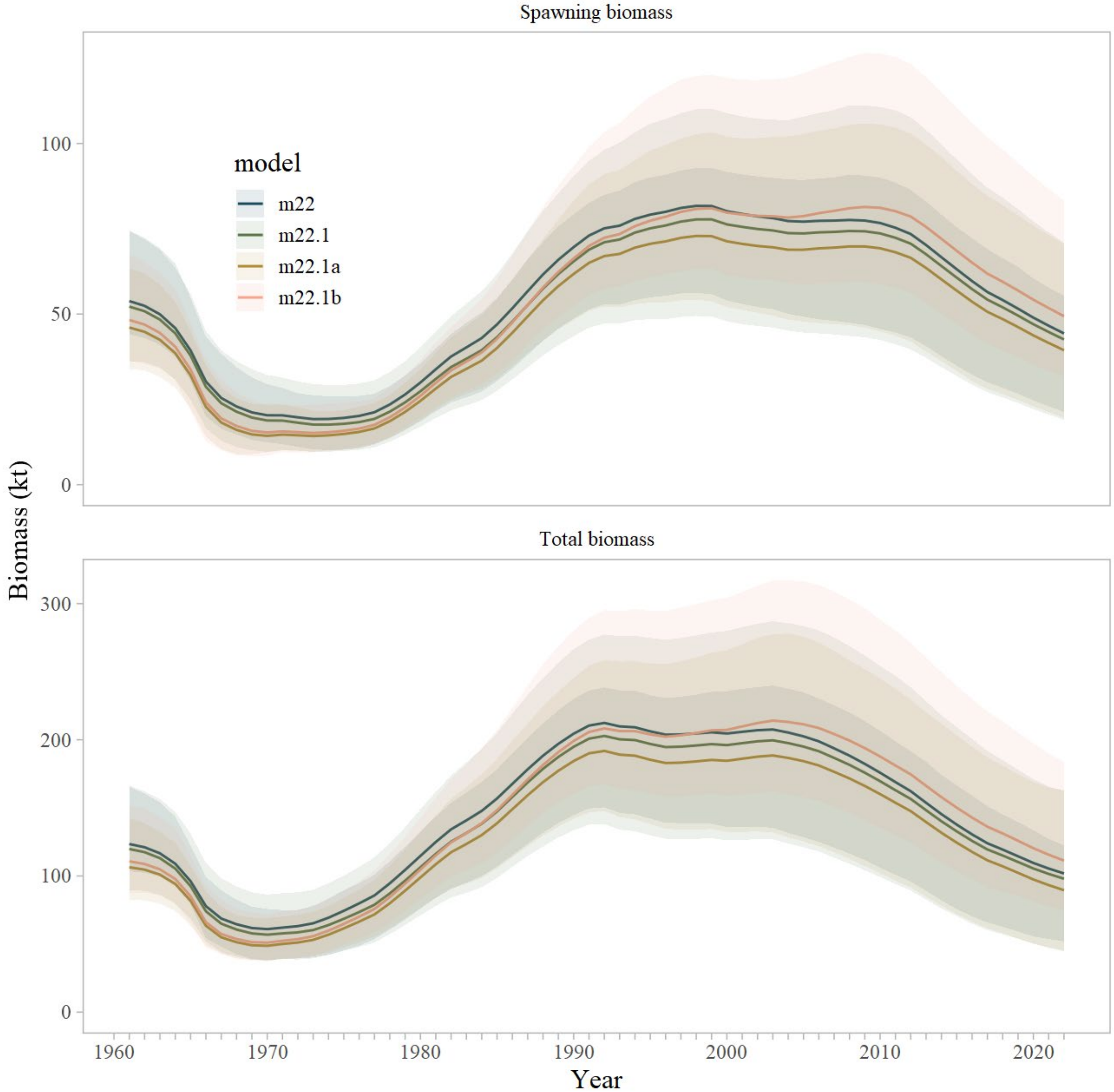

Figure 10-13. Comparisons of spawning and total biomass for different variants of model 22 (m22).

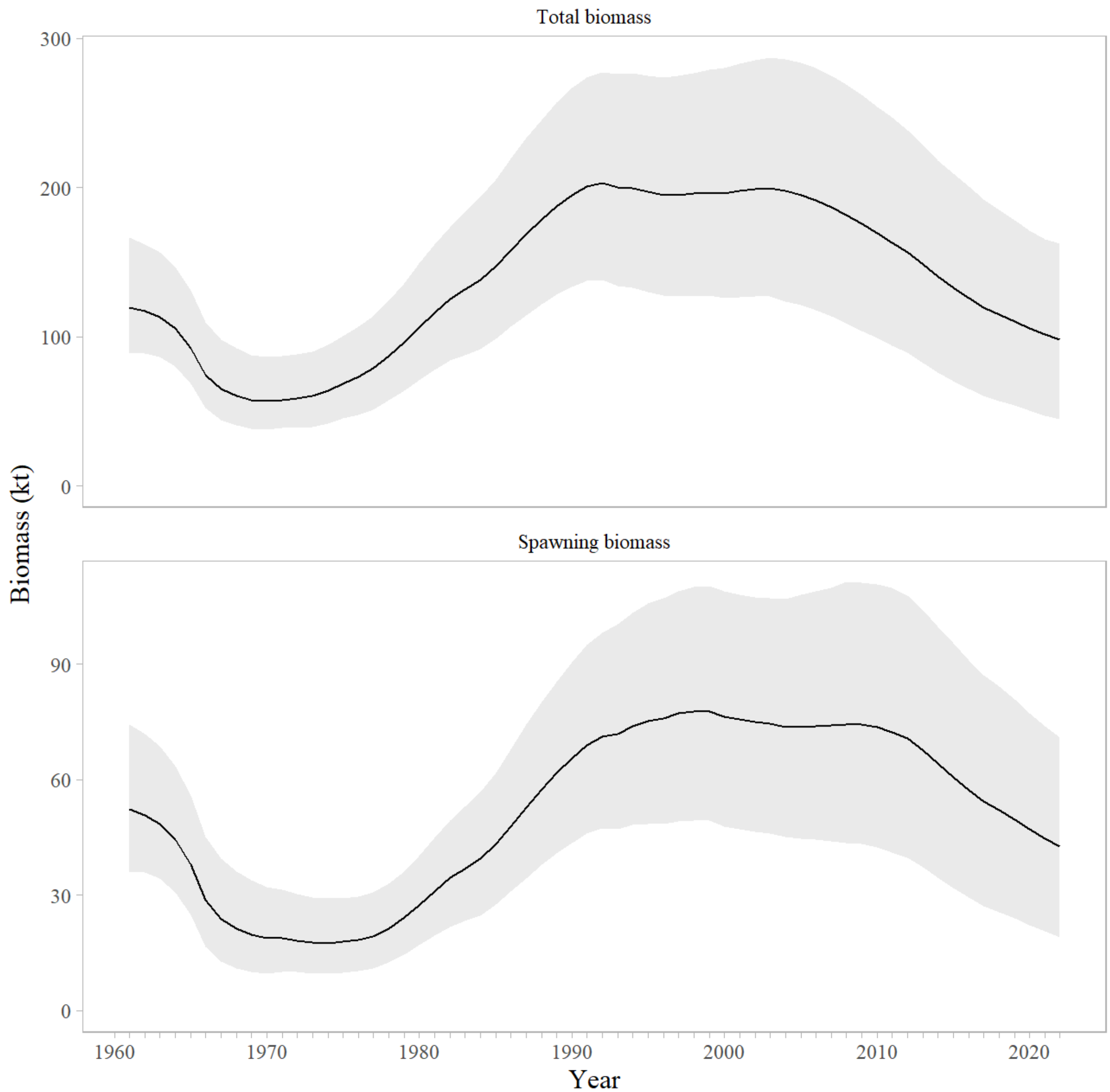

Figure 10-14. Model estimated total biomass and spawning biomass with 95% credible intervals determined by MCMC (shaded) for Gulf of Alaska northern rockfish.

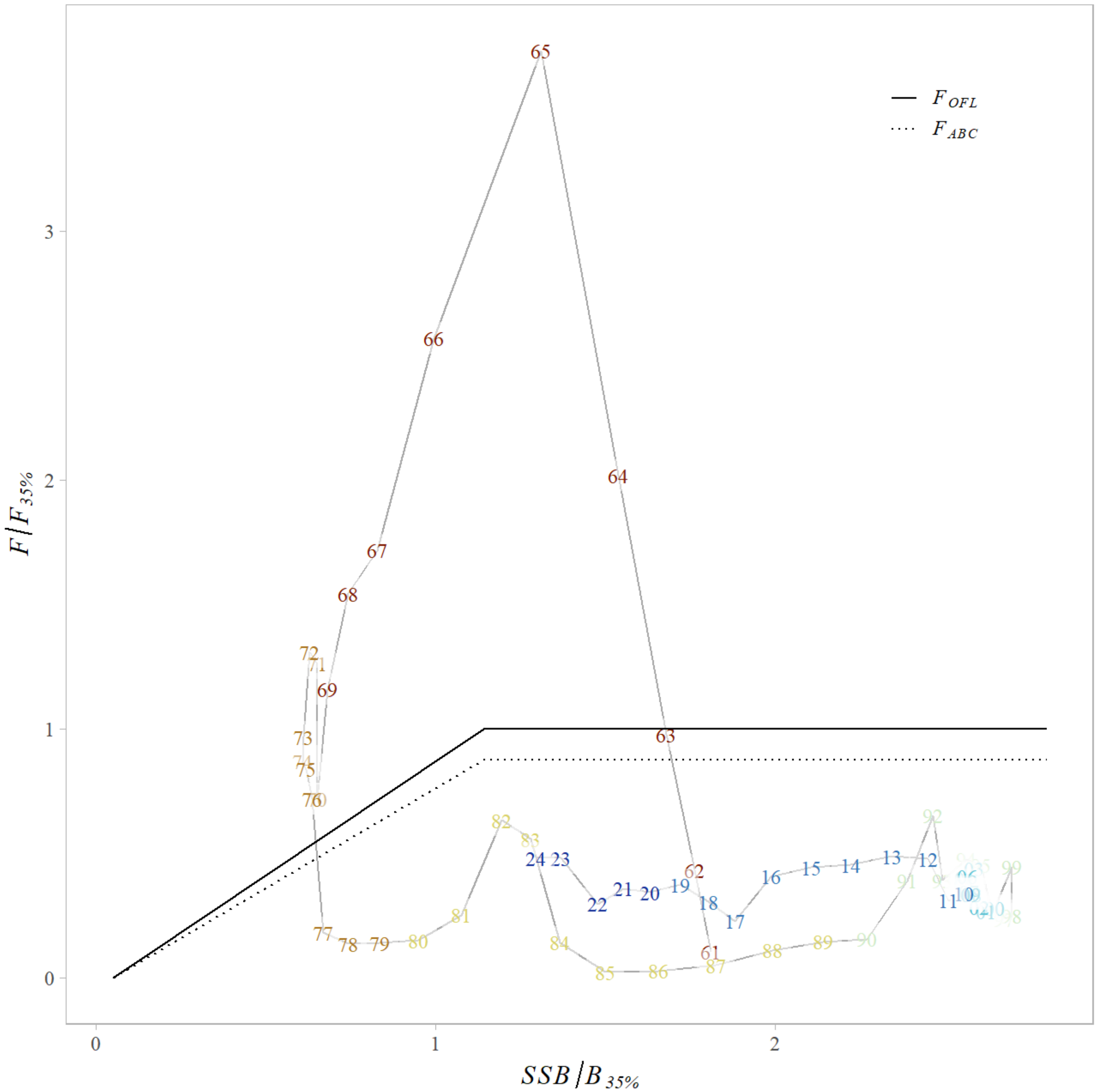

Figure 10-15. Time series of northern rockfish estimated spawning biomass (SSB) relative to B_(35%) and fishing mortality (F) relative to F_(35%) for author recommended model.

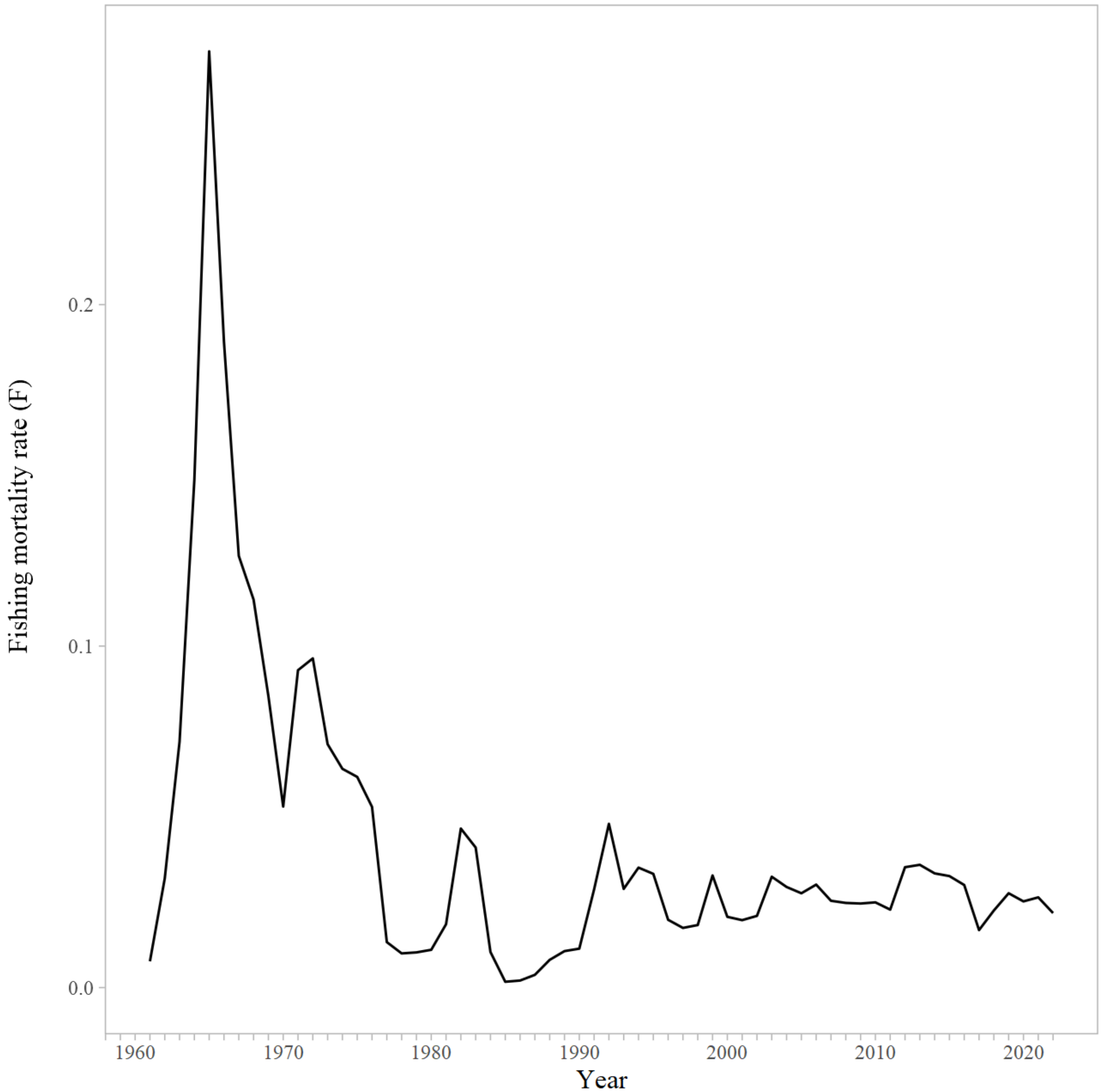

Figure 10-16. Time series of estimated fully selected fishing mortality for GOA northern rockfish from the 2022 model.

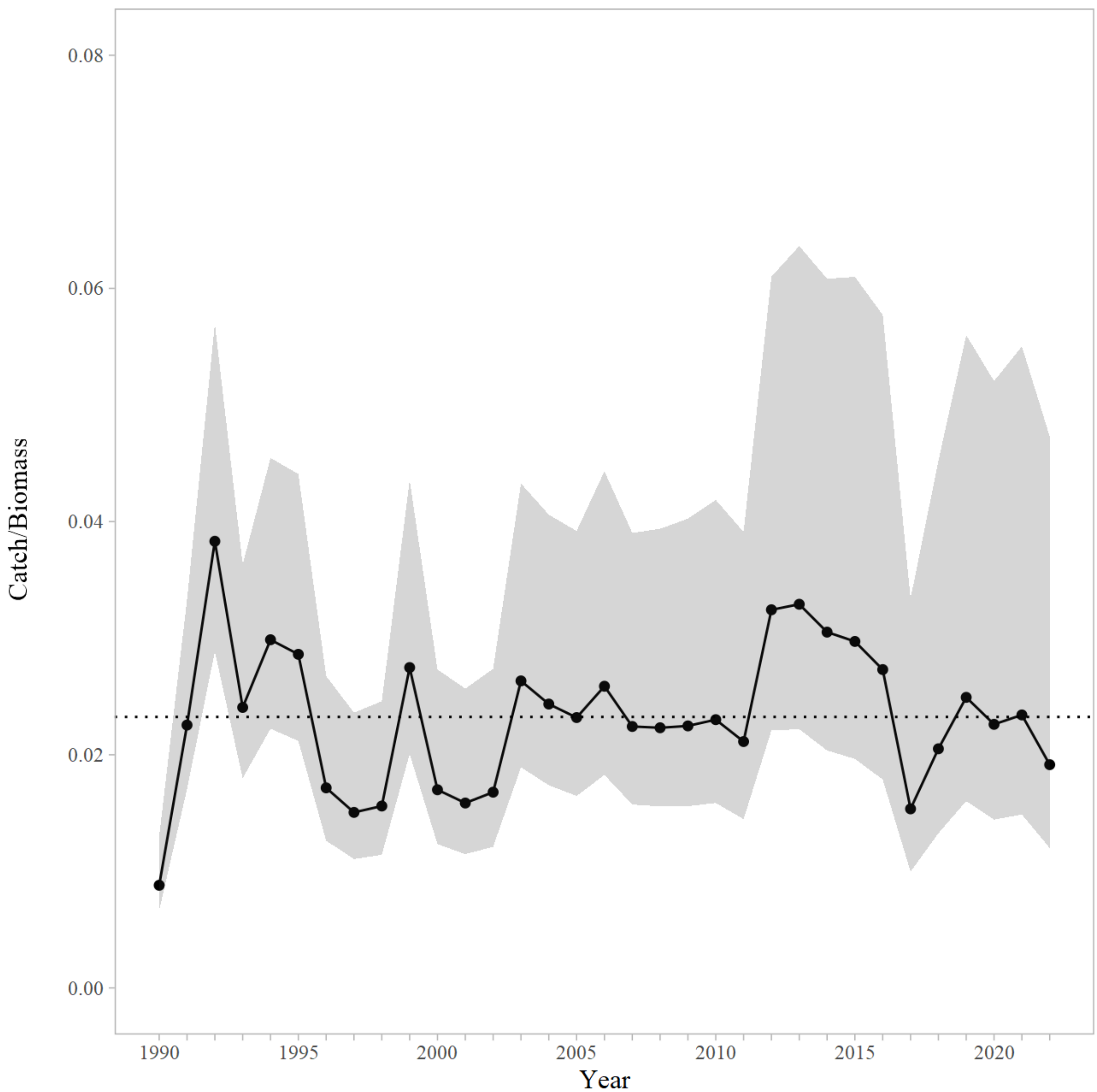

Figure 10-17. Gulf of Alaska northern rockfish catch/age 2+ biomass ratio with approximate 95% confidence intervals. Observed catch values were used for 1990-2022, the 2022 catch values were estimated using an expansion factor. The horizontal dashed line is the mean value for the entire dataset.

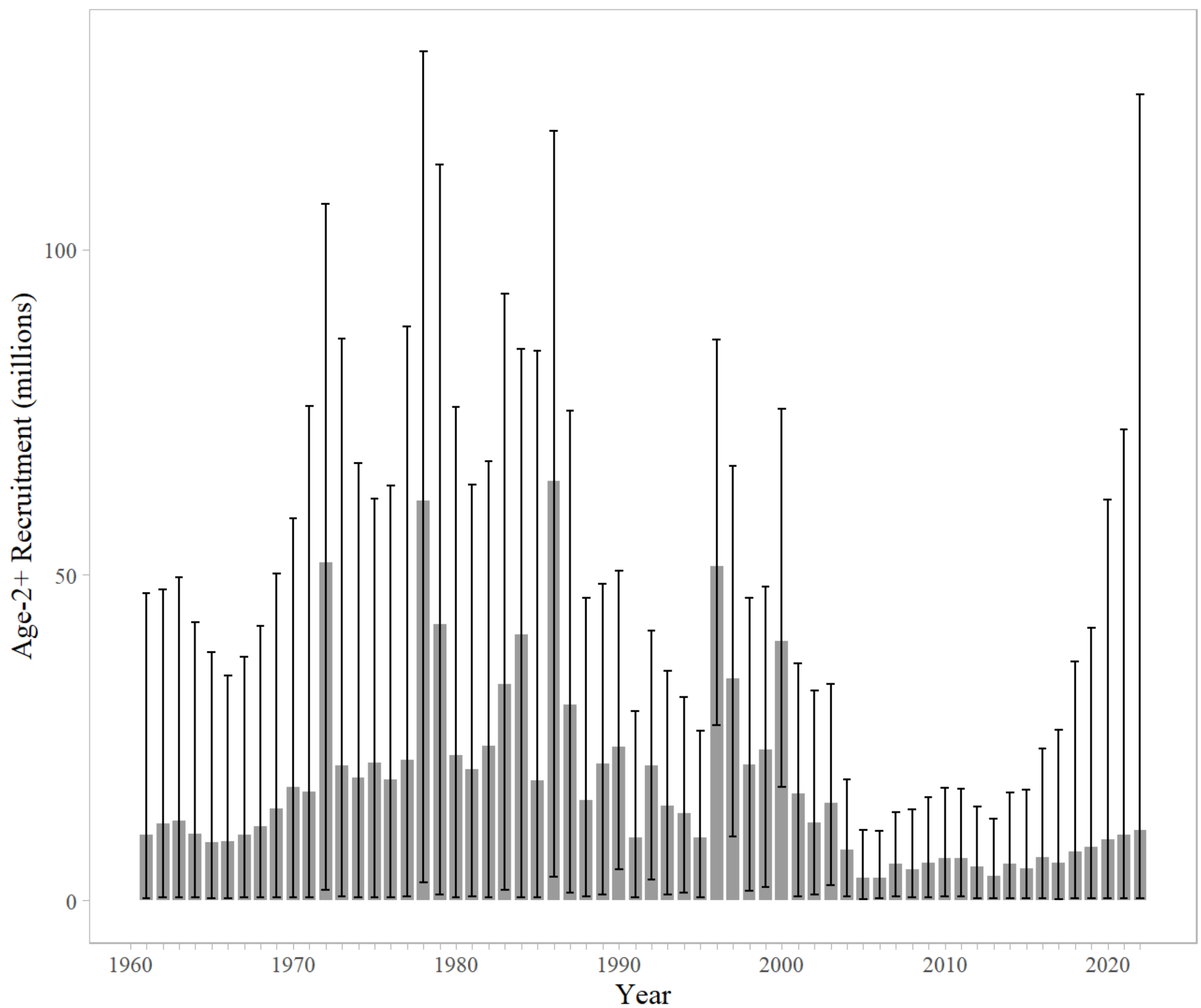

Figure 10-18. Estimates of age-4 recruitment with 95% credible intervals for GOA northern rockfish.

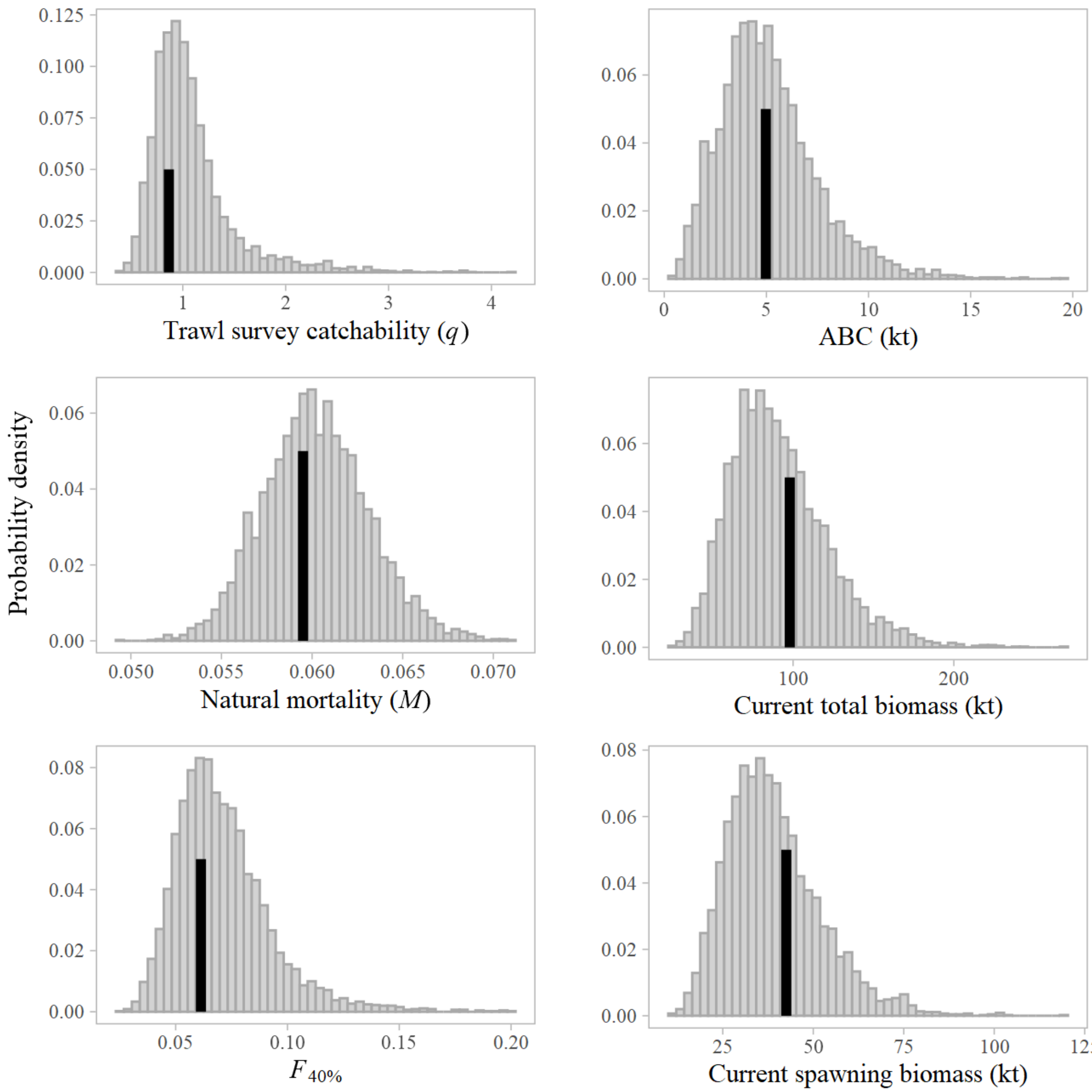

Figure 10-19. Histograms of estimated posterior distributions for key parameters derived (or estimated, in the case of *q*) from the MCMC for GOA northern rockfish. Vertical black lines represent the maximum likelihood estimate for comparison with the MCMC results.

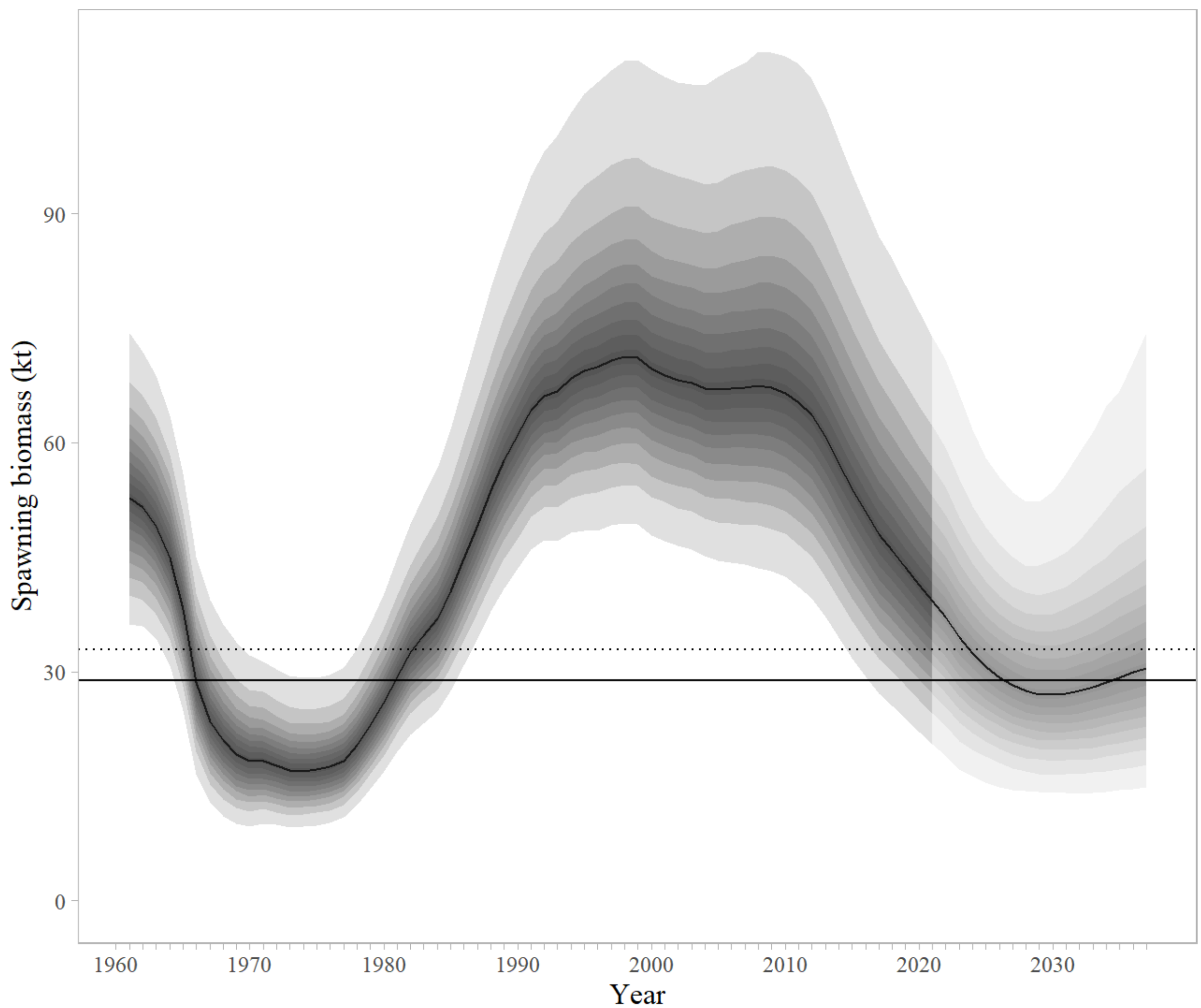

Figure 10-20. Median northern rockfish spawning stock biomass from MCMC simulations with Bayesian credible intervals including projections for 2023-2037, when managing under Scenario 2. Assumes the same average yield ratio forward in time. Dotted horizontal line is $B_{40\%}$ and solid horizontal line is $B_{35\%}$ based on recruitments from 1977-2018. Each shade is 5% of the posterior distribution.

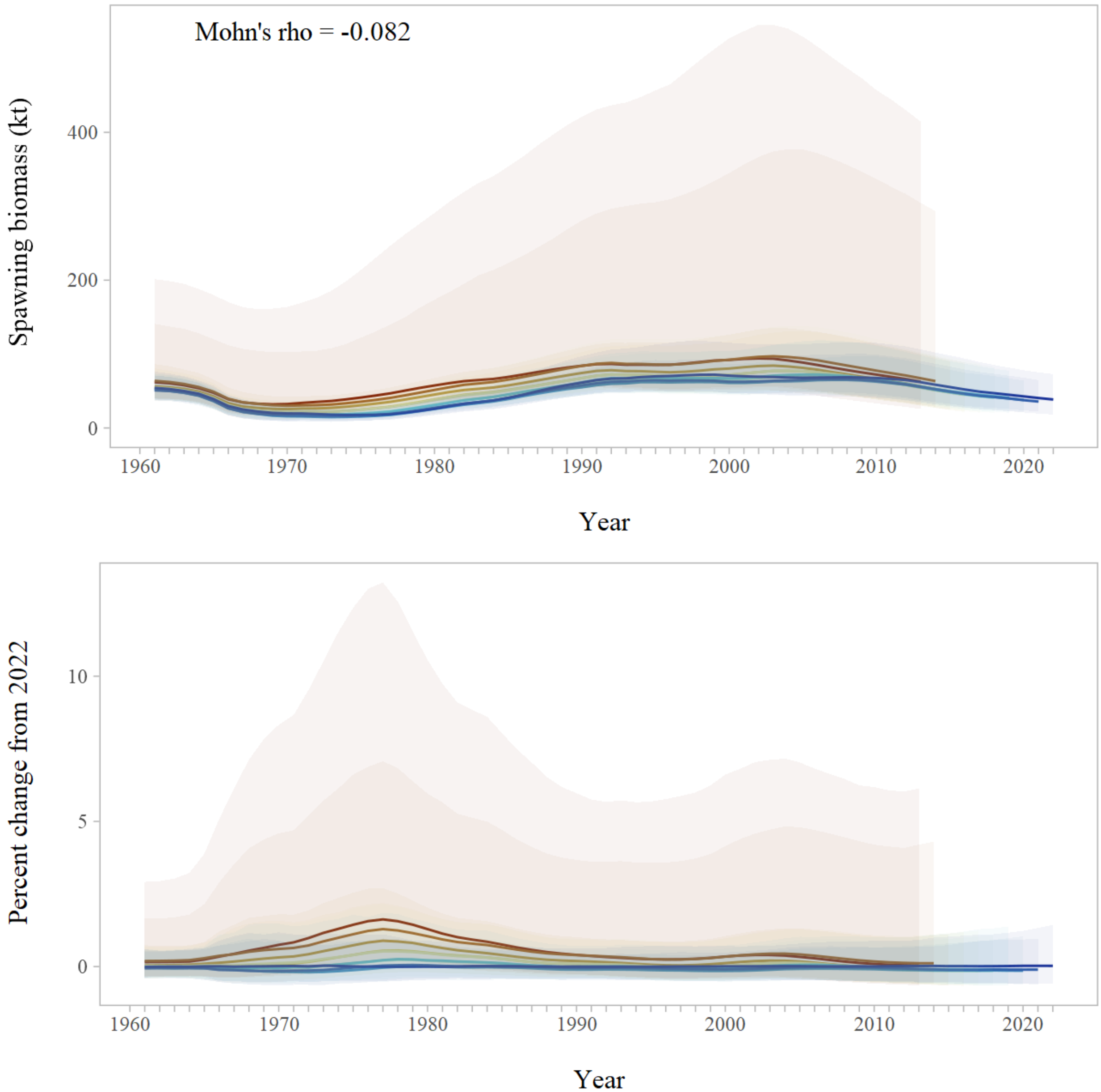

Figure 10-21. Retrospective peels of estimated female spawning biomass and total biomass for the past 10 years from the recommended model with 95% credible intervals derived from MCMC.

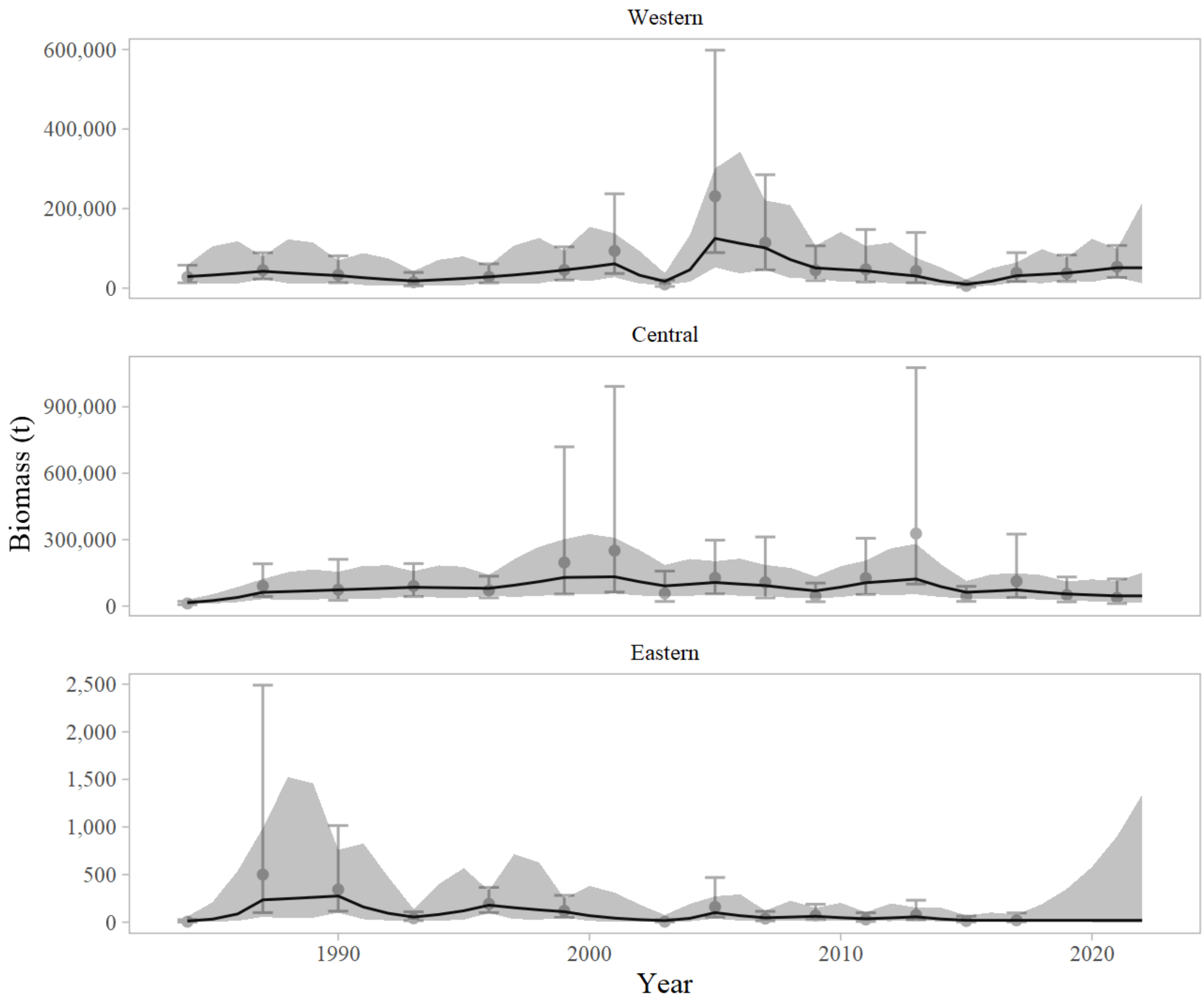

Figure 10-22. Time series of estimated fully selected fishing mortality for GOA northern rockfish from the 2022 model.

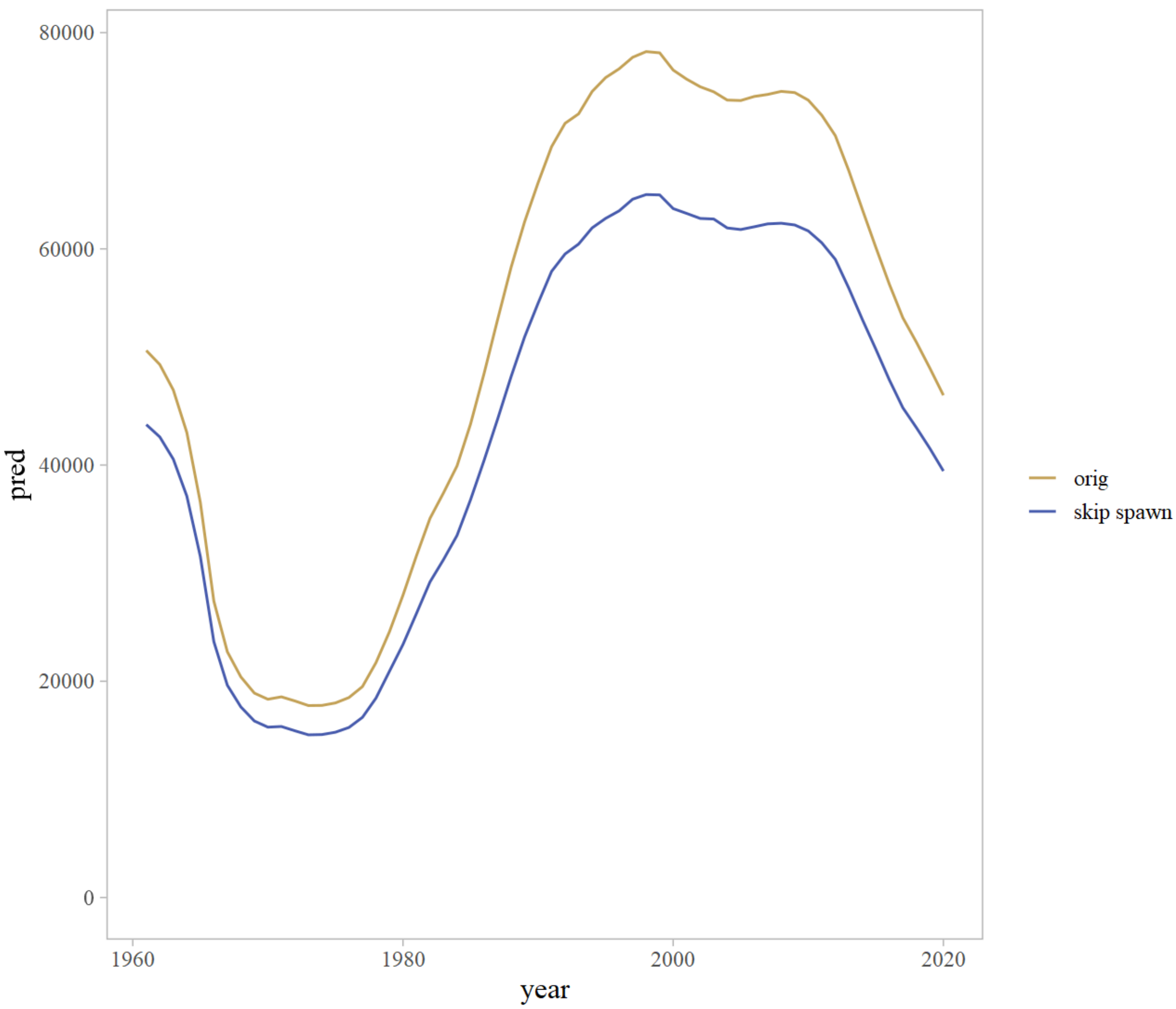

Figure 10-23. Estimate of spawning biomass if skip spawning at levels reported in Conrath 2019 occurred regularly.

Appendix 10a. Supplemental catch data

In order to comply with the Annual Catch Limit (ACL) requirements, a dataset has been generated to help estimate total catch and removals from NMFS stocks in Alaska. This dataset estimates total removals that occur during non-directed groundfish fishing activities. This includes removals incurred during research, subsistence, personal use, recreational, and exempted fishing permit activities, but does not include removals taken in fisheries other than those managed under the groundfish FMP. These estimates represent additional sources of removals to the existing Catch Accounting System estimates. For Gulf of Alaska (GOA) northern rockfish, these estimates can be compared to the research removals reported in previous assessments (Heifetz et al. 2009; Table 10 A-1). Northern rockfish research removals are minimal relative to the fishery catch and compared to the research removals of other species. The majority of research removals are taken by the Alaska Fisheries Science Center's (AFSC) biennial bottom trawl survey which is the primary research survey used for assessing the population status of northern rockfish in the GOA. Other research activities that harvest northern rockfish include longline surveys by the International Pacific Halibut Commission and the AFSC and the State of Alaska's trawl surveys. Recreational harvest of northern rockfish rarely occurs. Total removals from activities other than a directed fishery have been near 10 t for 2010 – 2017. The 2017 other removals is <1% of the 2018 recommended ABC of 4,529 t and represents a very low risk to the northern rockfish stock. Research harvests from trawl in recent years are higher in odd years due to the biennial cycle of the AFSC bottom trawl survey in the GOA and have been less than 10 t except in 2013 when 18 t were removed. These removals do not pose a significant risk to the northern rockfish stock in the GOA.

Table 10a-1. Total removals of Gulf of Alaska northern rockfish (t) from activities not related to directed fishing, since 2010. Trawl survey sources are a combination of the NMFS echo-integration, State of Alaska small-mesh, GOA bottom trawl surveys, and occasional short-term research projects. Other is longline, personal use, scallop dredge, and subsistence harvest.

Year	Other	Trawl	Recreational	Total
2010	<1	<1		<1
2011	<1	11		11
2012	<1	<1		<1
2013	<1	18	<1	18
2014	<1	<1		<1
2015	<1	8		8
2016	<1			<1
2017	<1	7		7
2018		<1		<1
2019	<1	5		5
2020	<1	<1		<1
2021		4		4

References

Heifetz, J., D. Hanselman, J. N. Ianelli, S. K. Shotwell, and C. Tribuzio. 2009. Gulf of Alaska northern rockfish. In Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska as projected for 2010. North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306 Anchorage, AK 99501. pp. 817-874.

Appendix 10b: VAST model-based abundance

Background

Model-based abundance indices have a long history of development in fisheries (Maunder and Punt 2004). We here use a delta-model that uses two linear predictors (and associated link functions) to model the probability of encounter and the expected distribution of catches (in biomass or numbers, depending upon the specific stock) given an encounter (Lo *et al*. 1992; Stefánsson 1996).
Previous research has used spatial strata (either based on strata used in spatially stratified design, or post-stratification) to approximate spatial variation (Helser *et al*. 2004), although recent research suggests that accounting for spatial heterogeneity within a single stratum using spatially correlated residuals and habitat covariates can improve precision for the wrestling index (Shelton *et al*. 2014).
Model-based indices have been used by the Pacific Fisheries Management Council to account for intra-class correlations among hauls from a single contract vessel since approximately 2004 (Helser *et al*. 2004).
Specific methods evolved over time to account for strata with few samples (Thorson and Ward 2013), and eventually to improve precision based on spatial correlations (Thorson *et al*. 2015) using what became the Vector Autoregressive Spatio-temporal (VAST) model (Thorson and Barnett 2017).

The performance of VAST has been evaluated previously using a variety of designs.
Research has showed improved performance estimating relative abundance compared with spatially-stratified index standardization models (Grüss and Thorson 2019; Thorson *et al*. 2015), while other simulation studies have shown unbiased estimates of abundance trends (Johnson *et al*. 2019).
Brodie *et al*. (2020) showed improved performance in estimating index scale given simulated data relative to generalized additive and machine learning models.
Using real-world case studies, Cao *et al*. (2017) showed how random variation in the placement of tows relative to high-quality habitat could be "controlled for" using a spatio-temporal framework, and OLeary *et al*. (2020) showed how combining surveys from the eastern and northern Bering Sea within a spatio-temporal framework could assimilate spatially unbalanced sampling in those regions. Other characteristics of model performance have also been simulation-tested although these results are not discussed further here.

Settings used in 2021

The software versions of dependent programs used to generate VAST estimates were:

```
R (>=4.1.0), INLA (21.02.23), TMB (1.7.18), TMBhelper (1.3.0), VAST (3.6.1),
FishStatsUtils (2.8.0)
```

We used a Poisson-link delta-model (Thorson 2018) involving two linear predictors, and a gamma or lognormal distribution to model positive catch rates. We extrapolated catch density using 3705 m (2 nmi) X 3705 m (2 nmi) extrapolation-grid cells; this results in 36,690 extrapolation-grid cells for the eastern Bering Sea, 15,079 in the northern Bering Sea and 26,510 for the Gulf of Alaska (some Gulf of Alaska analyses eliminated the deepest stratum with depths >700 m because of sparse observations, resulting in a 22,604-cell extrapolation grid). We used bilinear interpolation to interpolate densities from 750 "knots" to these extrapolation-grid cells (i.e, using `fine_scale=TRUE` feature); knots were approximately evenly distributed over space, in proportion to the dimensions of the extrapolation grid. We estimated geometric anisotropy (how spatial autocorrelation declines with differing rates over distance in some cardinal directions than others), and included a spatial and spatio-temporal term for both linear predictors. To facilitate interpolation of density between unsampled years, we specified that the spatio-temporal fields were structured over time as an AR(1) process (where the magnitude of autocorrelation was estimated as a fixed effect for each linear predictor). However, we did not include any temporal correlation for intercepts, which we treated as fixed effects for each linear predictor and year. Finally, we used epsilon bias-correction to correct for retransformation bias (Thorson and Kristensen 2016).

Diagnostics

We checked model fits for evidence of non-convergence by confirming that (1) the derivative of the marginal likelihood with respect to each fixed effect was sufficiently small and (2) that the Hessian matrix was positive definite.
We then checked for evidence of model fit by computing Dunn-Smyth randomized quantile residuals (Dunn and Smyth 1996) and visualizing these using a quantile-quantile plot within the DHARMa R package.
We also evaluated the distribution of these residuals over space in each year, and inspected them for evidence of residual spatio-temporal patterns.

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